Development of a Fracture Processes Facility at DUSEL Homestake

1. Scientific objectives
2. Experimental approach
3. Expected results
4. Facilities

Workgroup

Deformation processes affected by natural and man-induced changes of in-situ conditions

- *faulting mechanisms*
- *fault healing, sealing and triggering*
- *fluid-driven and mixed mode fracture propagation*
- *fracture interaction, fracture energy scaling*
- *thermal effects*
- *biogeochemical reactions, microbial interactions*
- *and related*

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Steve Martel
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Ze'ev Reches
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Steve Glaser
Rob Jeffrey
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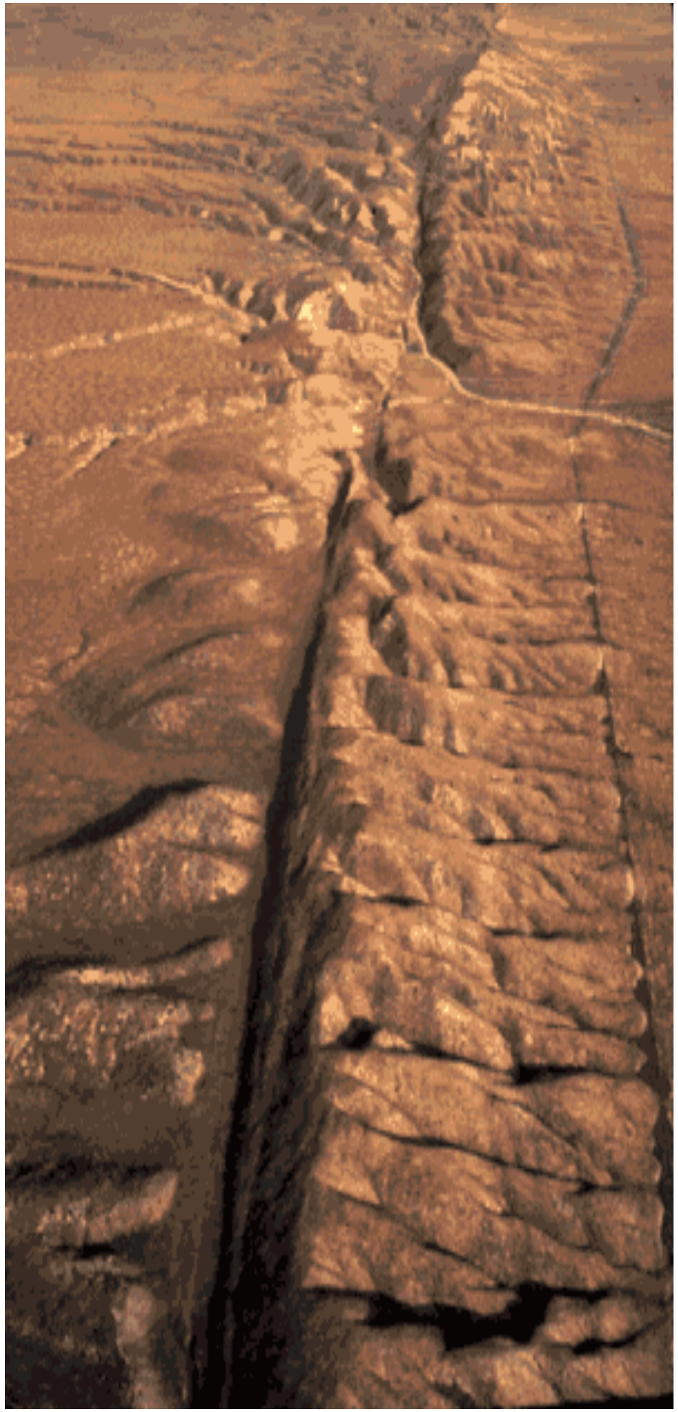
Eric Westman
Joe Labuz
Leonid Germanovich
Ali Shafiee

FAULT EXPERIMENT



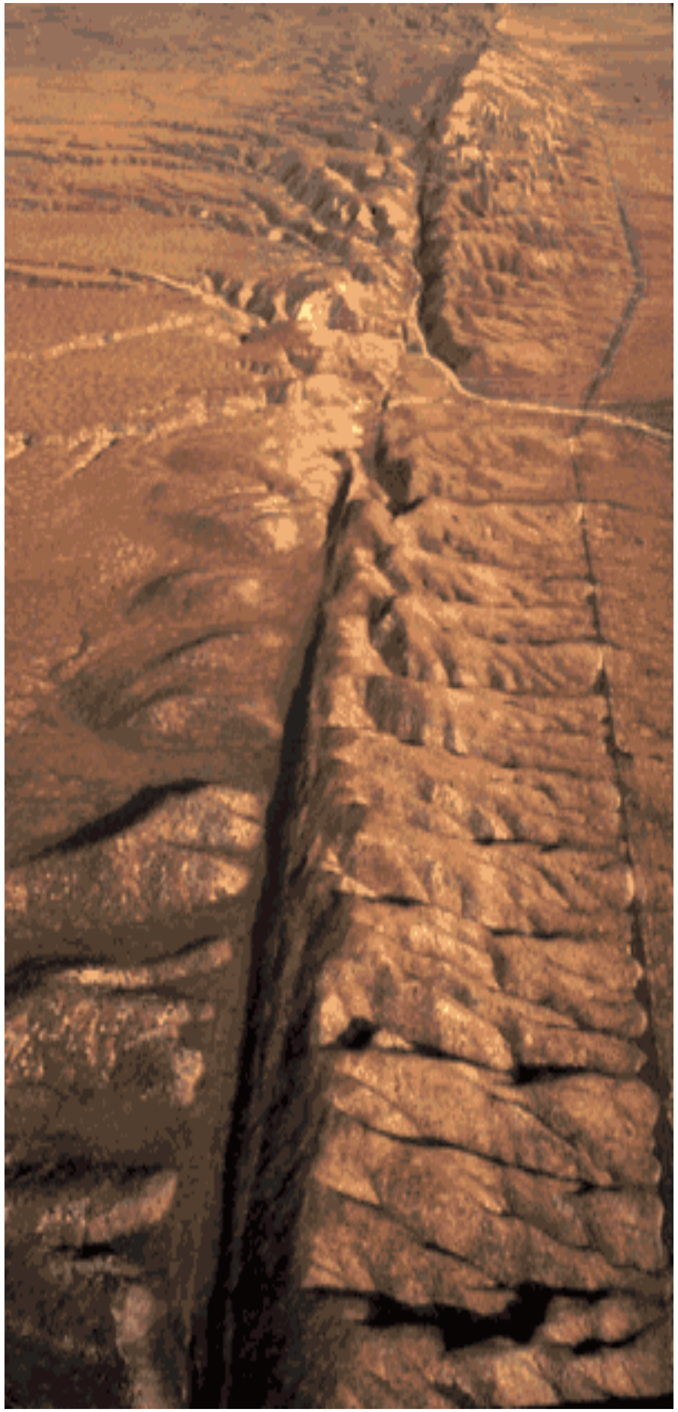
Hypotheses:

- Faulting processes change with scale.
- Small laboratory experiments are inherently incomplete representations of real faults.
- Large experiments are needed to advance understanding of faulting and earthquakes

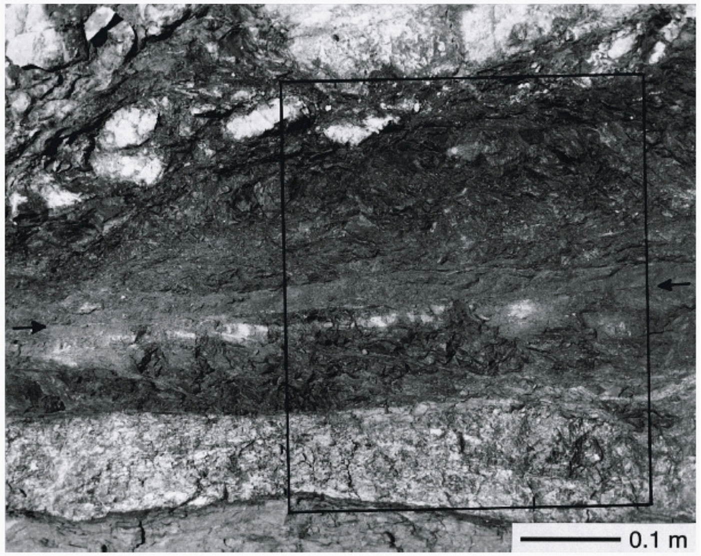
FAULTING PROCESSES

- Fault nucleation, localization, reactivation, propagation, arrest
- Seismic response
- Dynamic weakening

  Slip nucleating on "weak" patches and propagating through "strong" rock
- Friction laws
- Propagation of faults in intact rock
- Gouge development
- Fluid effects
- Sealing and healing
- Effects on microbial ecosys
- Many others ...

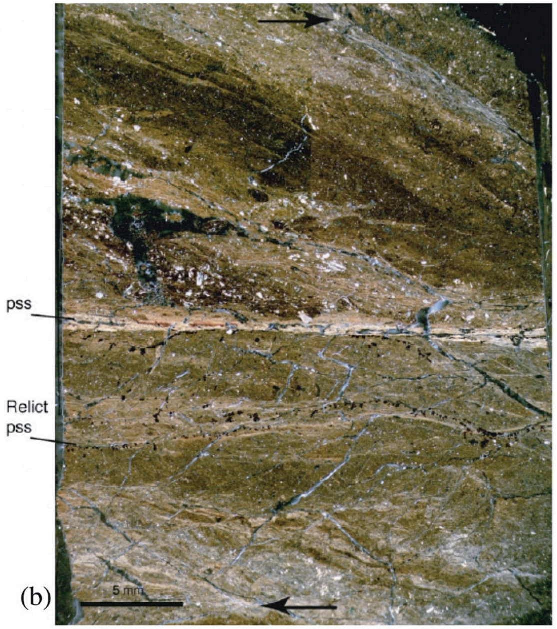


EARTHQUAKE MECHANISMS



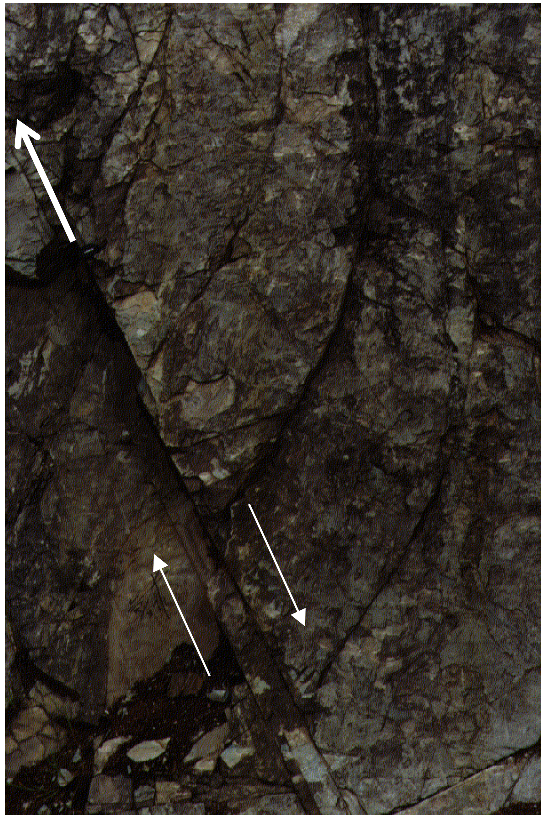
(a)

Chester and Chester [1998]

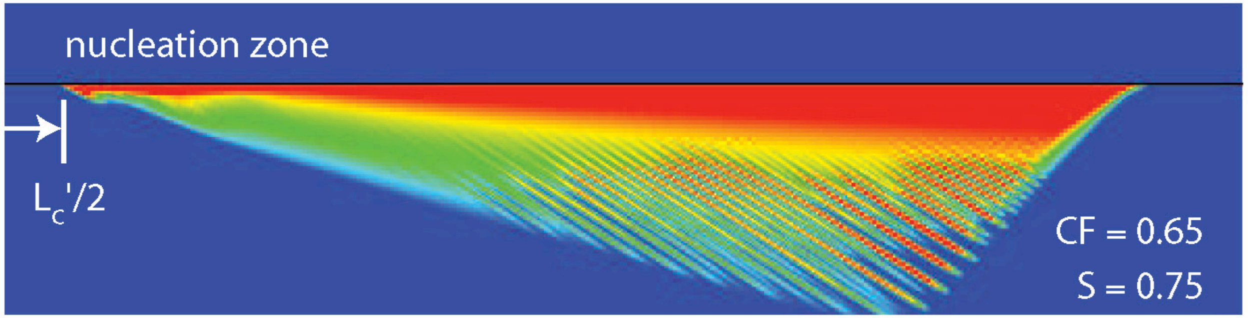


(b)

Chester et al. [2003]

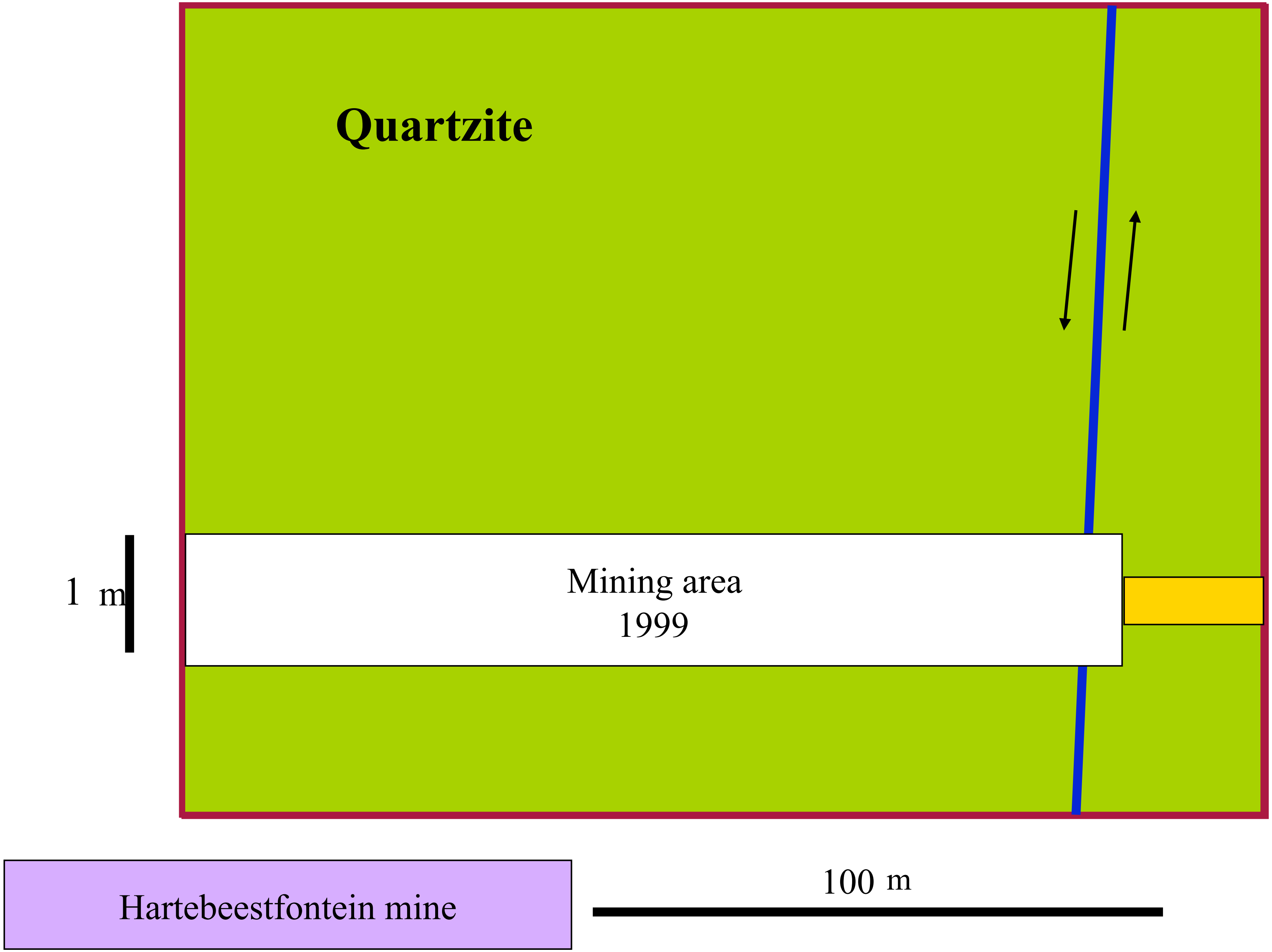


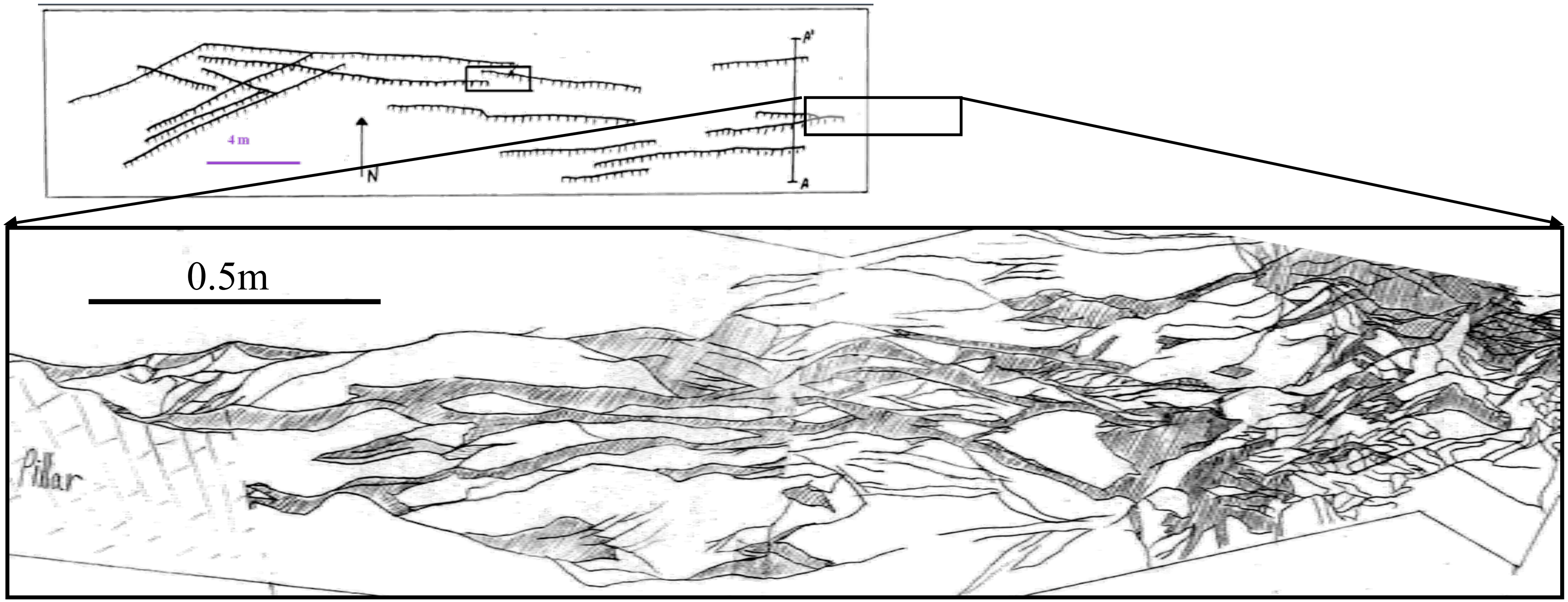
1 m



Templeton and Rice [2008]

Fault Nucleation [*Reches et al.*]



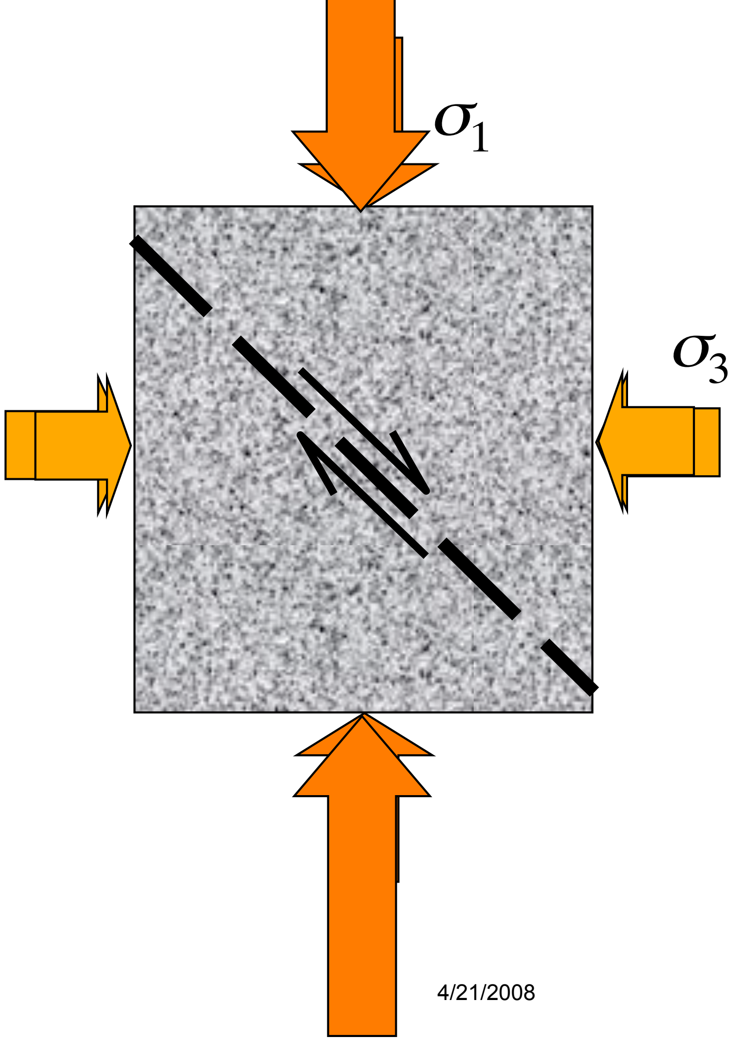

4 m
N
A'
A
0.5m
Pillar

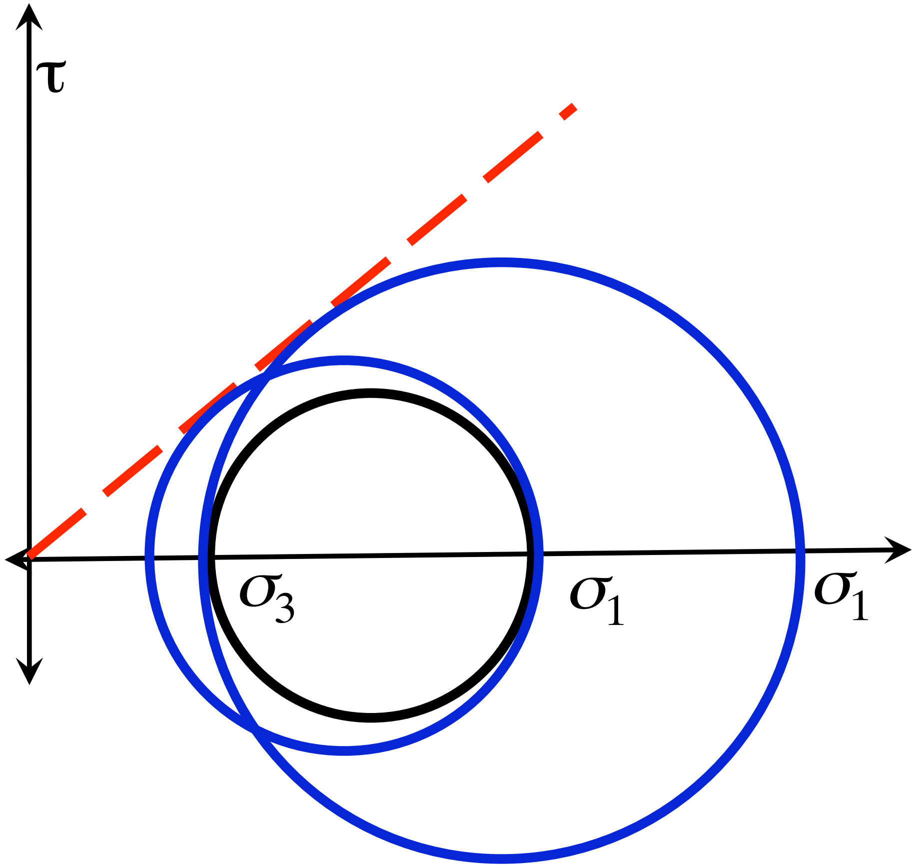
FAULT EXPERIMENT

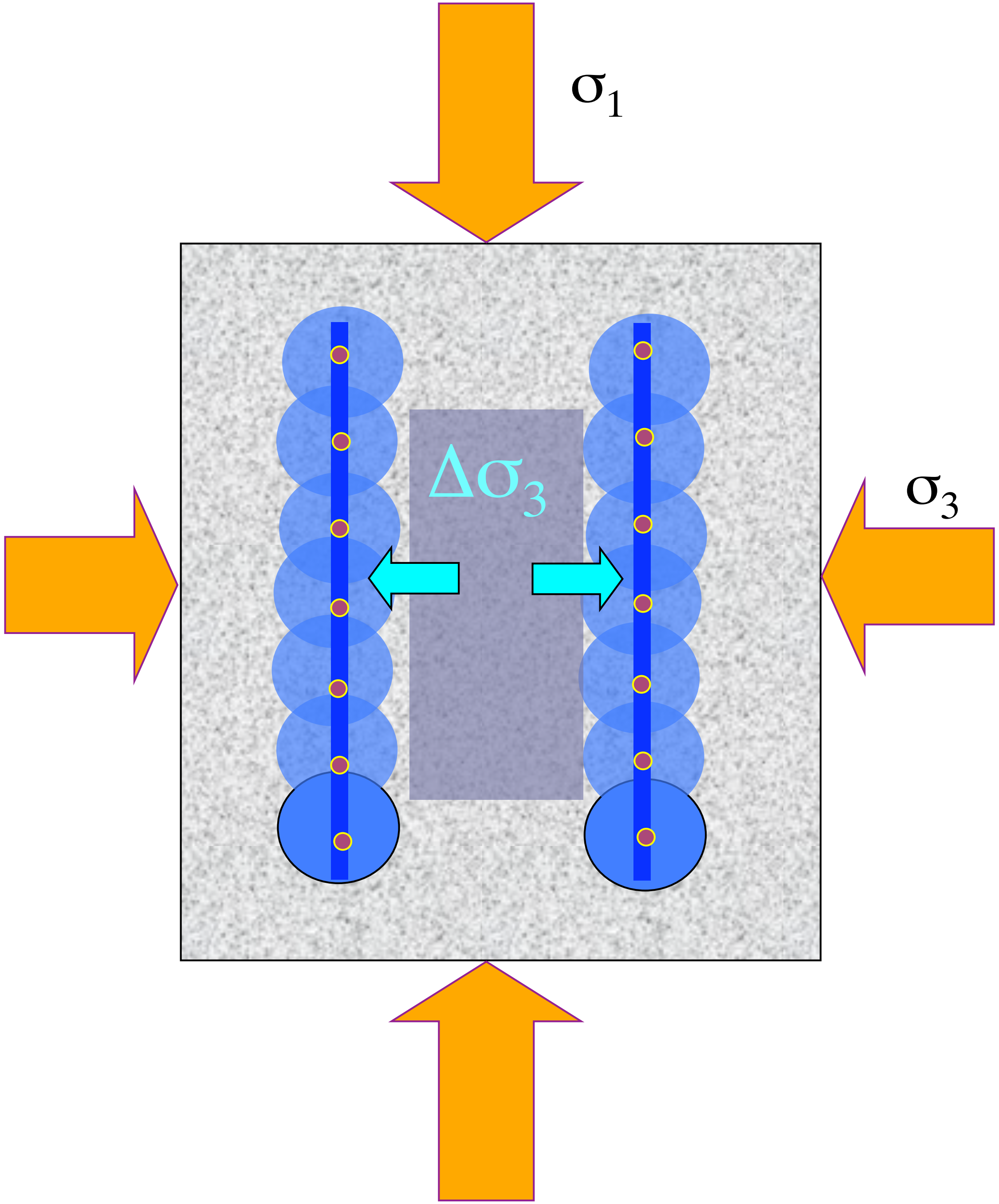
Approach

Utilize large, *natural* in-situ stresses – currently, the only option

Create failure by *reducing* existing load

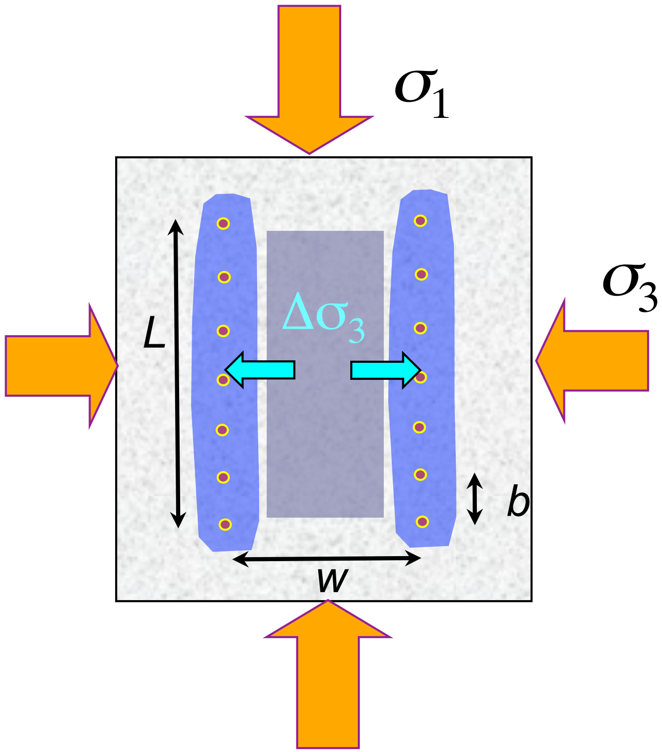






Concept

1. Create a pair of parallel lines of boreholes or slots normal to σ_3
2. Cooling by ΔT reduces σ_3 and allows controlled modification of stress state between lines
3. Reduce σ_3 between boreholes until failure occurs



Scaling

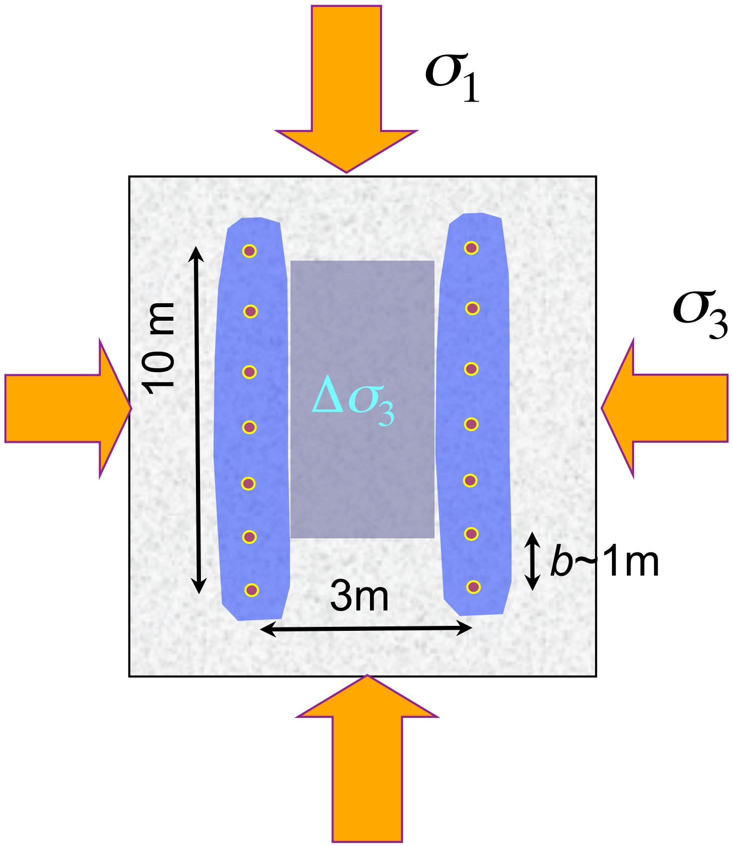
Will the stress change enough to cause failure?

$$\Delta\sigma_3 \approx \frac{2\alpha\Delta T\sqrt{at}}{L}$$

Will it be fast enough to be practical?

$$t \approx \frac{1}{a}\sqrt{\frac{b}{\alpha\Delta T}}$$

EXAMPLE



Will it be fast enough to be practical?

$$t \approx 11 \text{ days}$$

Will the stress change enough?

$$\Delta\sigma_3 \approx -22\text{MPa}$$

Stress change reqirefd to cause failure per Mohr-Coulomb condition, $\phi = 40°$

$$\Delta\sigma_{3@failure} \approx -17\text{MPa}$$

ASSUME

Depth ~ 1 km in generic rock

E ~ 10^{11} Pa

α ~ 10^{-5} °C^{-1}

a ~ 10^{-6} m^2/s

ρ ~ 2600 kg/m^3

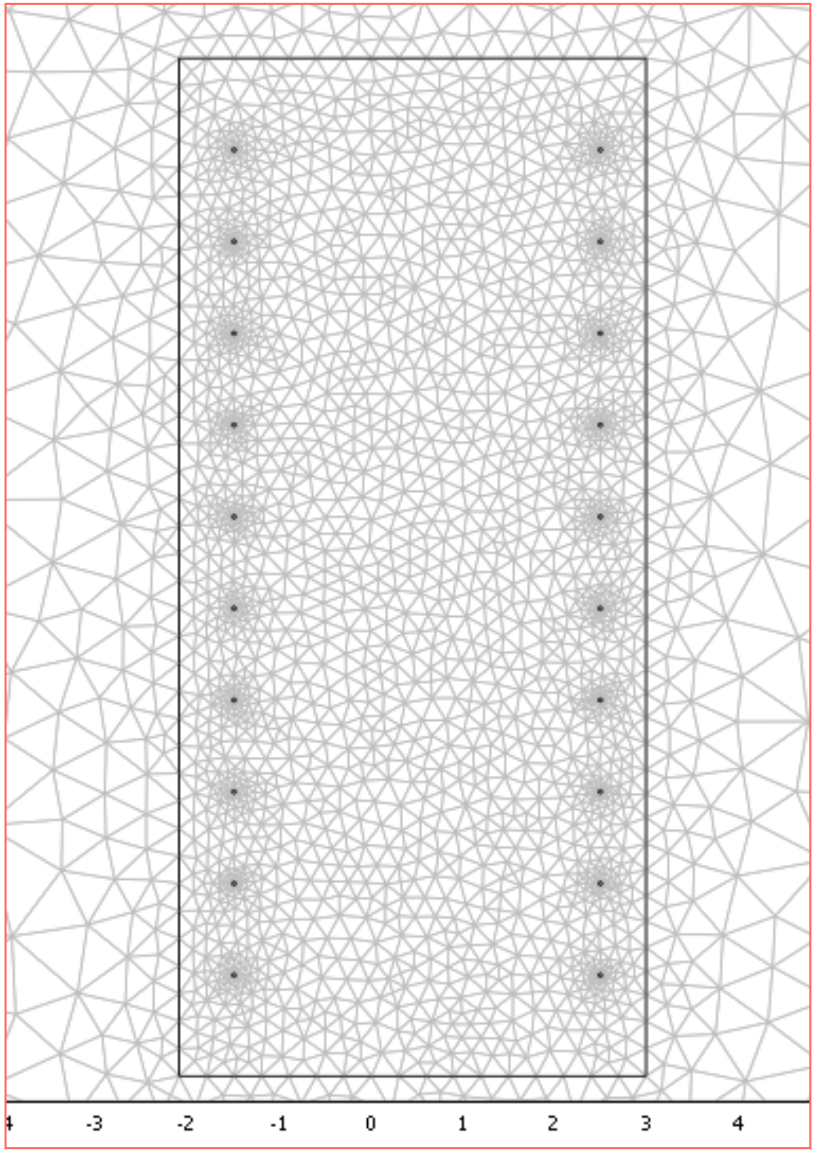
σ_1 ~ 25 MPa

σ_3 ~ 23 MPa

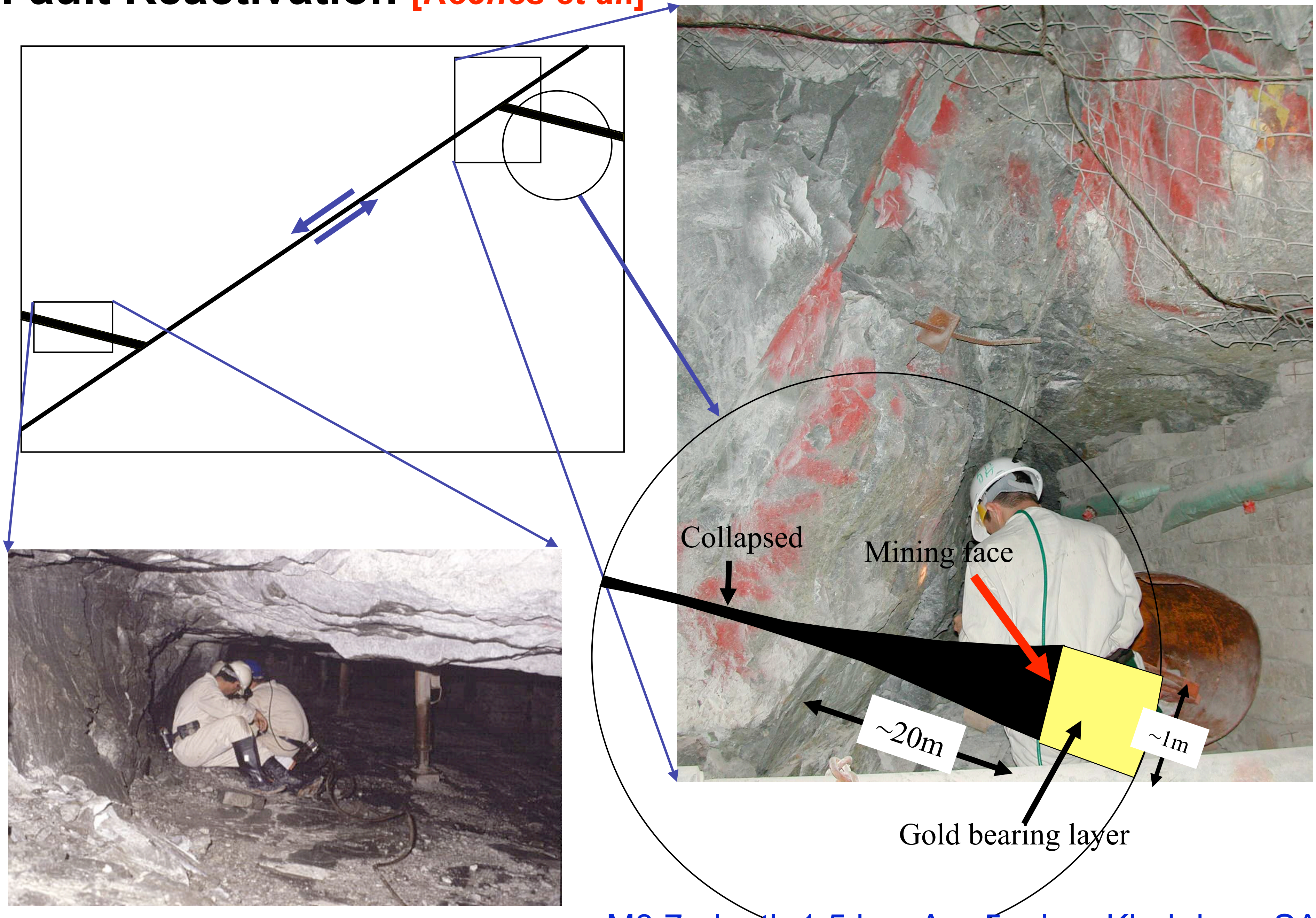
ΔT ~ 10^2 °C

FEASIBILITY

- Scaling is promising
- Preliminary numerical results confirm scaling results, demonstrate versatility
- Ongoing work for planning DUSEL
  - 3-D modeling
  - Design analyses
  - Lab experiments
  - Small-scale field experiment (?)

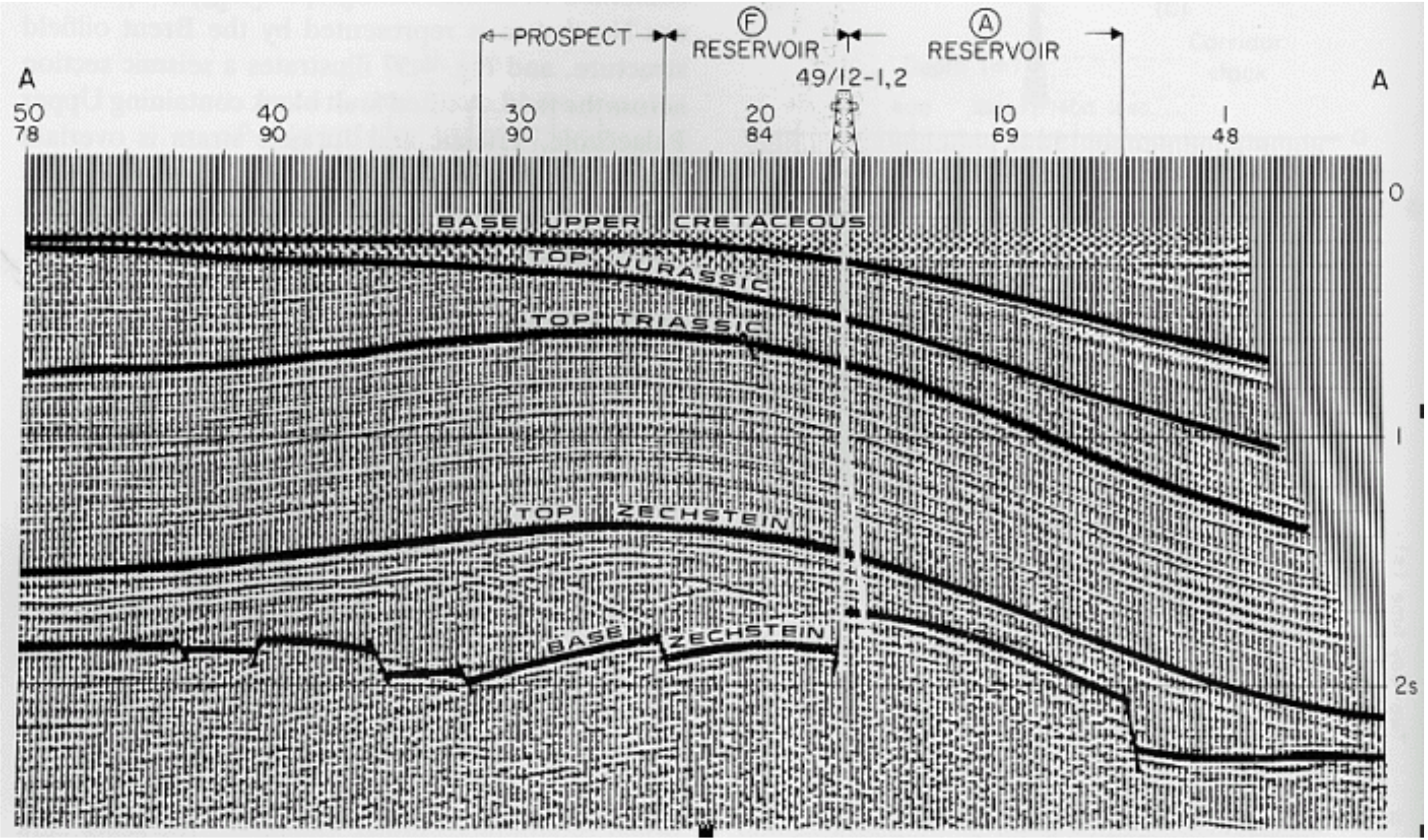


Fault Reactivation [*Reches et al.*]



M3.7, depth 1.5 km, Arm5 mine, Klerkdorp, SA

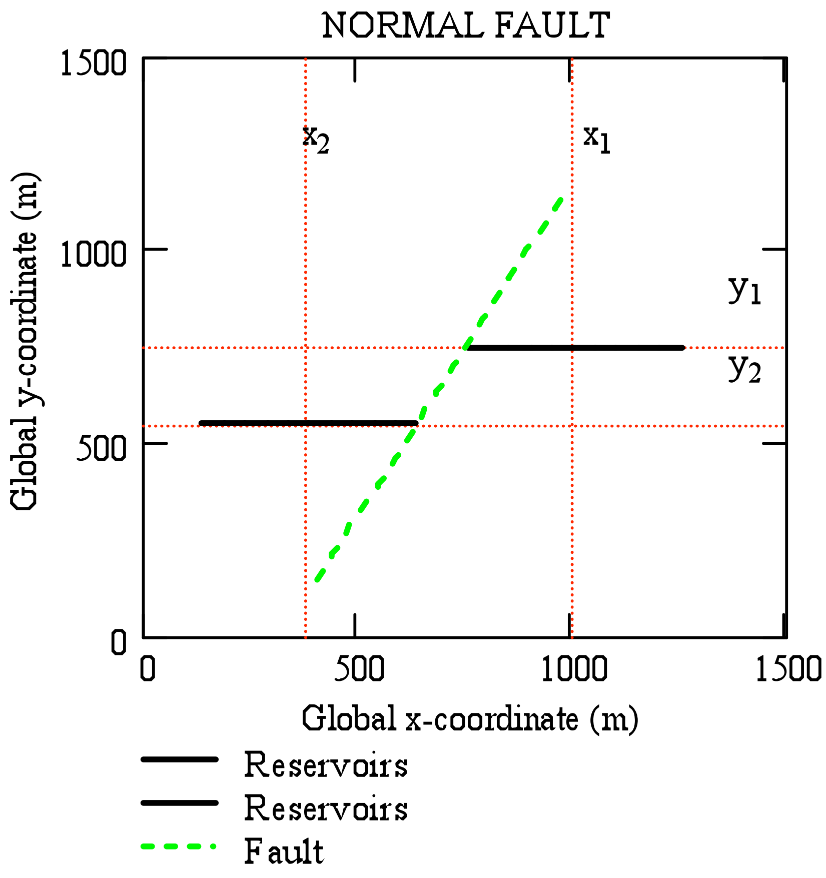
PRODUCTION INDUCED SEISMICITY AND WELL SHEARING

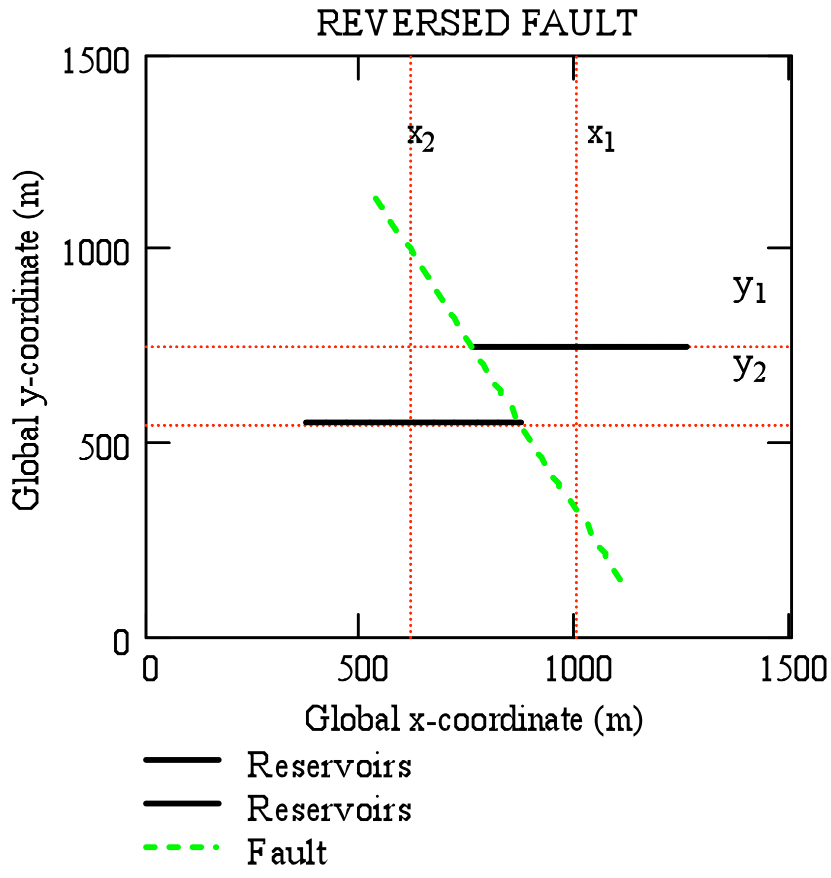


[*Kearey and Brooks*, 1991]

TWO DEPLETING RESERVOIRS

Normal and Reversed Faults





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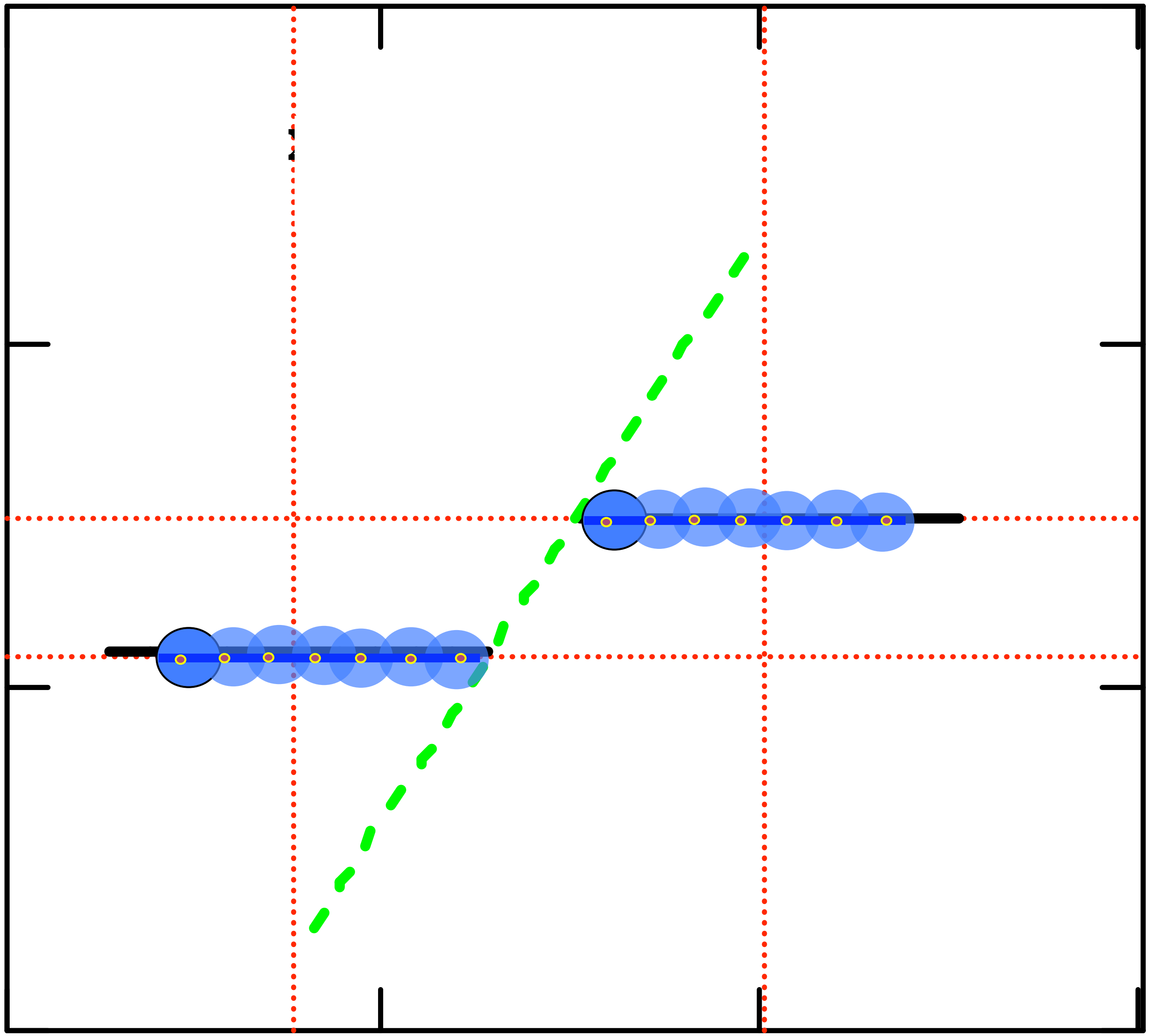
Normal and Reversed Faults

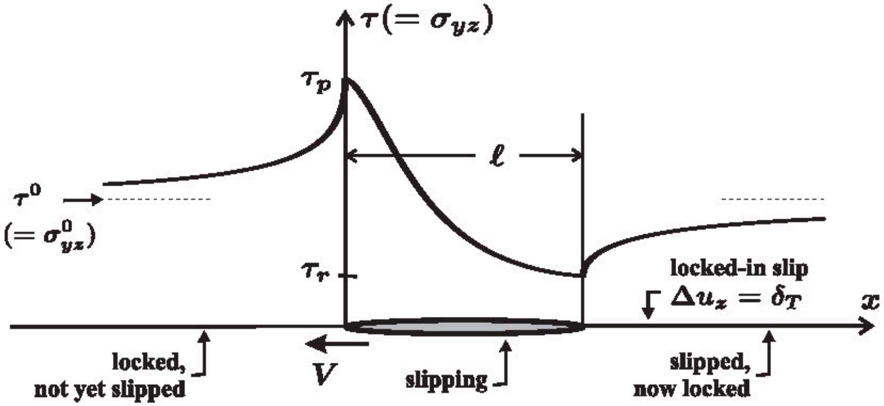


Dynamic Slip Propagation

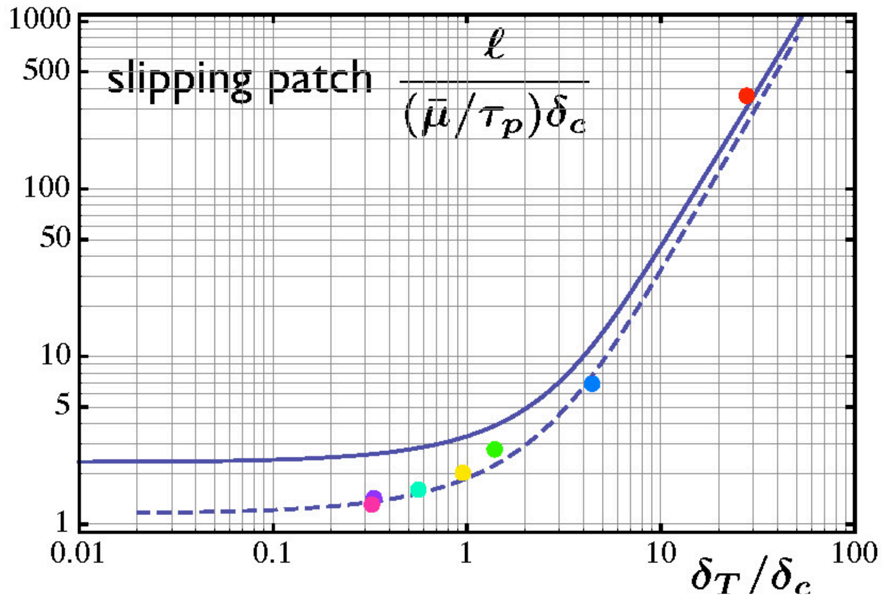
- “Weaken” a patch ~ 1 m to initiate dynamic rupture
- E.g., slip initiation on a pressurized patch ~1 m
- Need fault zone ~10 m (or greater)
- Crack growth (from ~1 to ~10 m) vs. self-healing slip pulse propagation (~0.1 -- 1 m)
- Understanding earth-quake source mechanisms
- E.g., flash heating [*Rice*, 1999], thermal pressurization [*Lachenbruch*, 1980], and gouge lubrication [*Reches*, 2009]

Dynamic Slip Propagation

Garagash [2009]



Event & depth range	δ (m)	ℓ (km)	V (km / s)	$\overline{\Delta\sigma}_p$ (MPa)
Michoacan 1988 10 – 35 km (est)	2.8	13	2.6	1.4
Borah Peak 1983 0 – 15 km (est)	0.96	1.7	2.9	2.6
San Fernando 1971 3 – 15 km	1.4	2.2	2.8	4.
Imperial Valey 1979 0 – 10 km	0.56	2.6	2.6	1.3
Morgan Hill 1984 0 – 12 km	0.44	0.8	2.8	3.2
N. Palm Springs 1986 1 – 12 km	0.33	1.2	3	1.2
Coyote Lake 1979 3 – 10 km	0.32	1.4	2.8	2.2



- Self-healing rupture
- Two dynamic wakening mechanisms
- Flash heating and thermal pressurization

Why is DUSEL a good place for this experiment?

1. At large scales, objectives can only be achieved by manipulating in situ conditions and depths, and then directly observing results.

2. Such experiments require substantial and specialized sub-surface infrastructure over many years.

3. Excavating host rock in the vicinity of created faults and fractures -- mining through.

Matjhabeng Mine, Eland Shaft, Welkom, South Africa [Reches et al., 2002].

Fracture Processes Facility

Facility

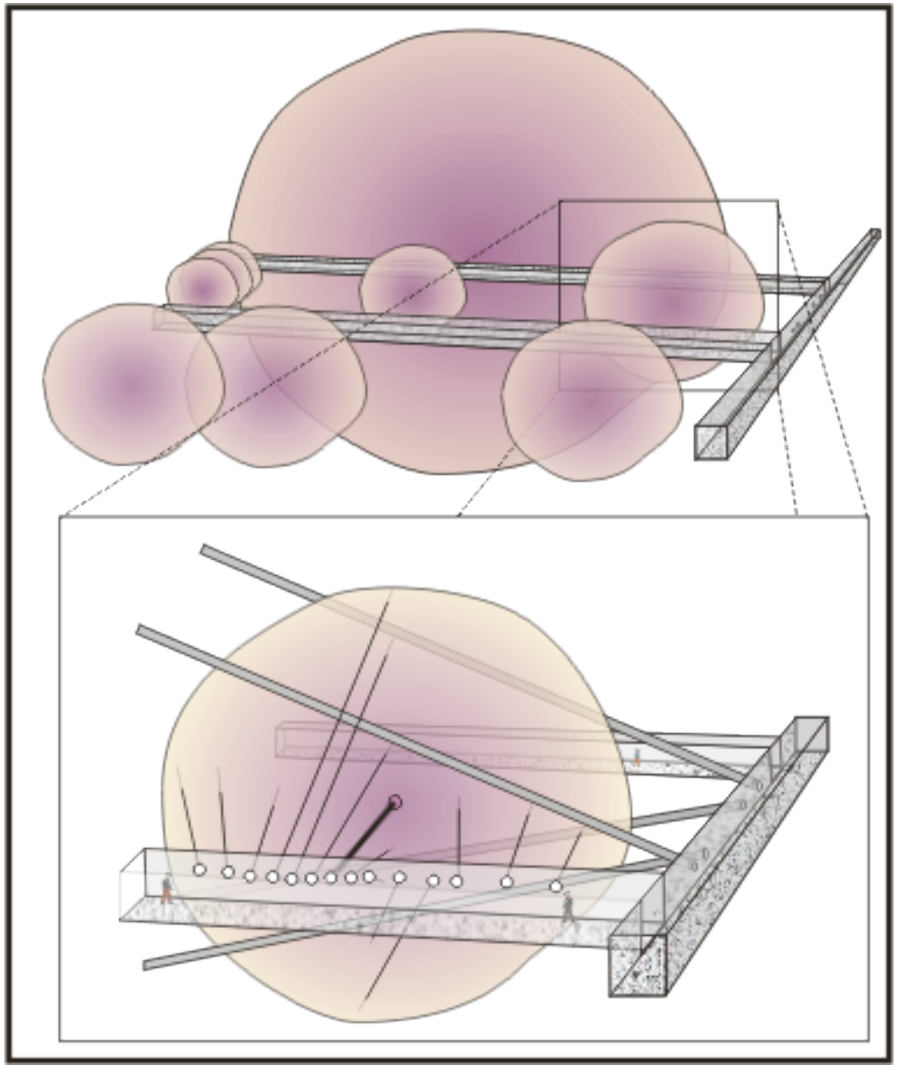
- 2-3 locations
- 4850 L and 7400 L
- Fresh vs. preexisting faults

Cost

- under NSF cap

ENO

- Demonstration/development experiments at 300 ft level



SUITE OF EXPERIMENTS

1. Fault experiment
2. Fracture propagation and scaling of fracture energy

   Jointly with *Minnesota*
3. Transport and reactions

   Incorporated in Fault Experiment

   Jointly with *THMCB facility*
4. Microbiological processes during fracture

   Incorporated in Fault Experiment
5. Fluid flow in networks

   Jointly with ecohydrology facility

APPROACH

Create idealized fractures for basic processes, then move to natural fractures

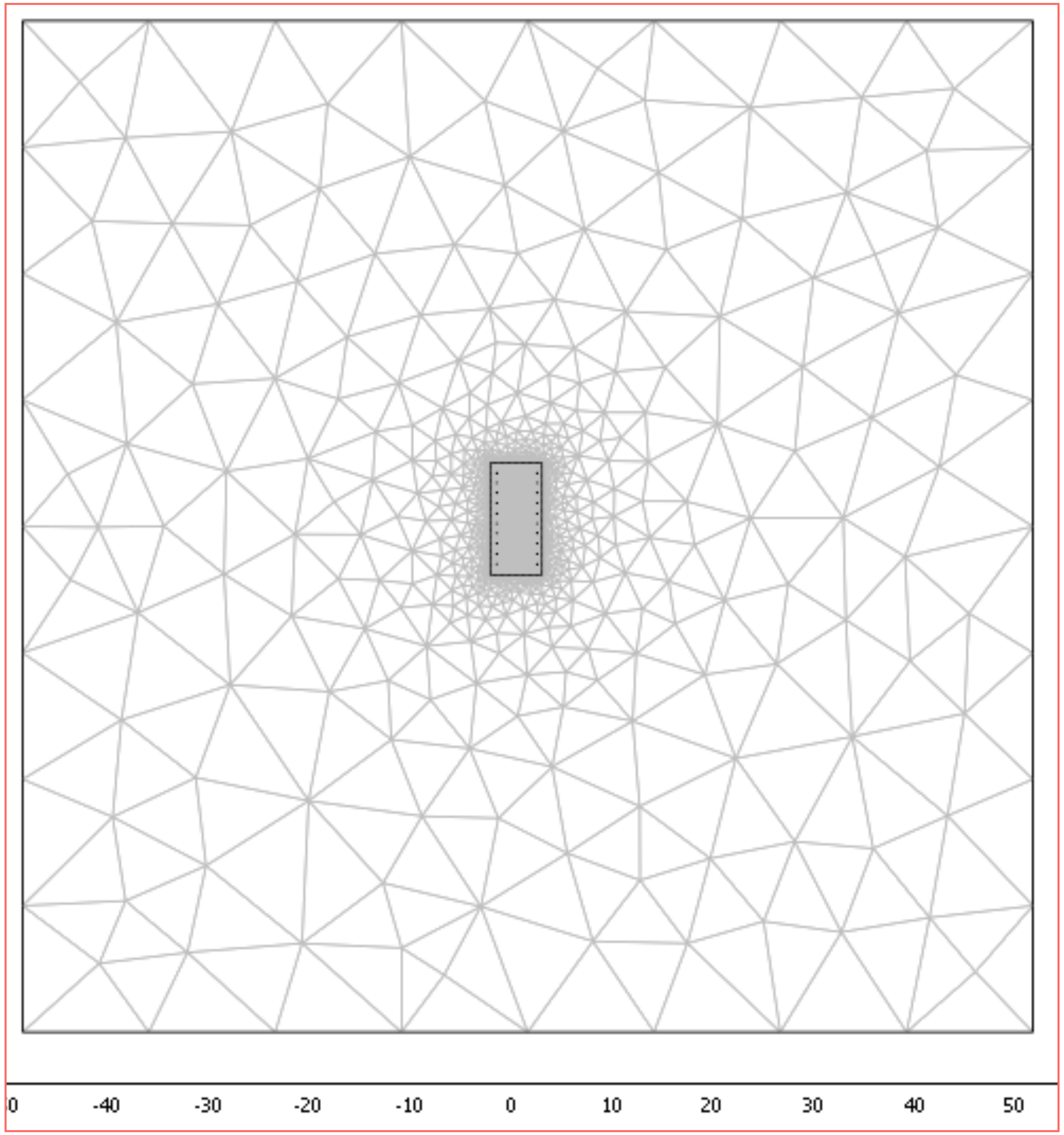
- Hydraulic fracturing to evaluate Mode I propagation
- Change stresses using thermal technique → ”designer fractures”
- Small stress change
    - a. stress and permeability (up to critical stress)
    - b. create cross-cutting hfrx → development of percolating networks
- Large stress change
    - a. slip on existing fractures
    - b. gouge development
    - c. fault growth

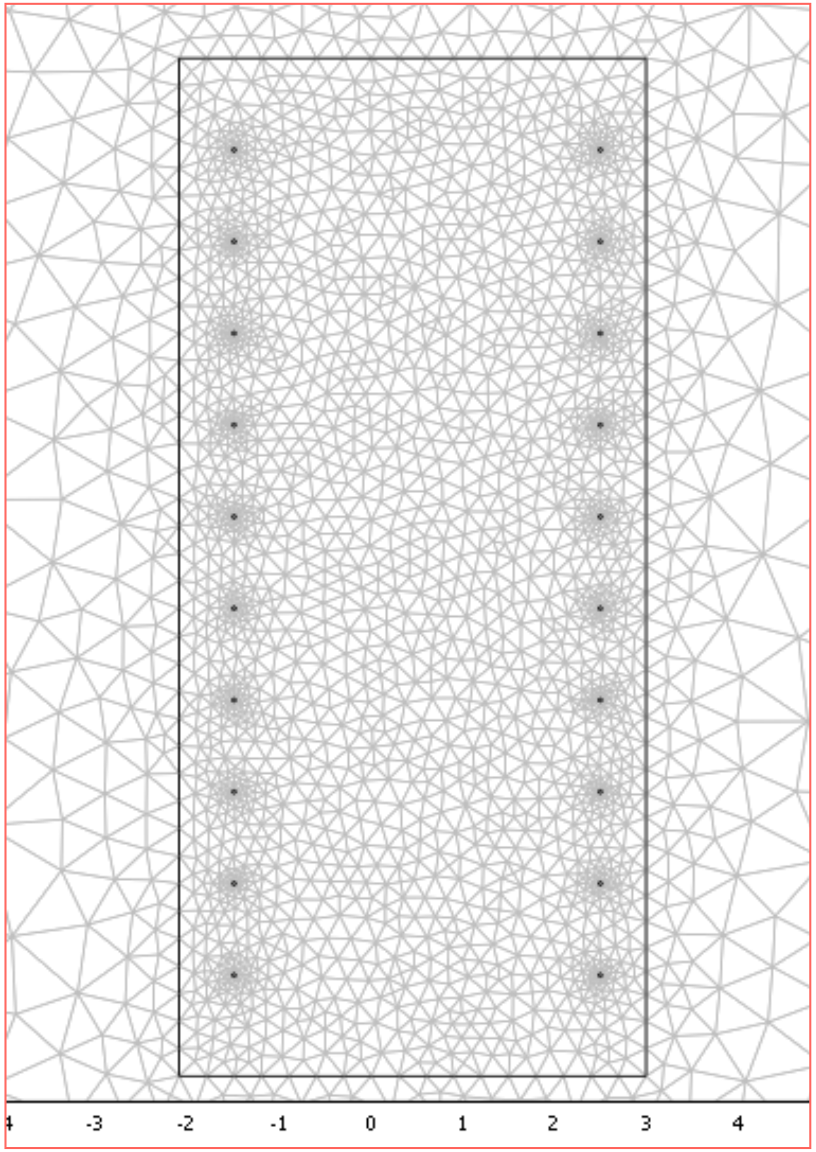
Use well understood/designed fractures and fracture networks to:

- Characterize scaling of fracture energy

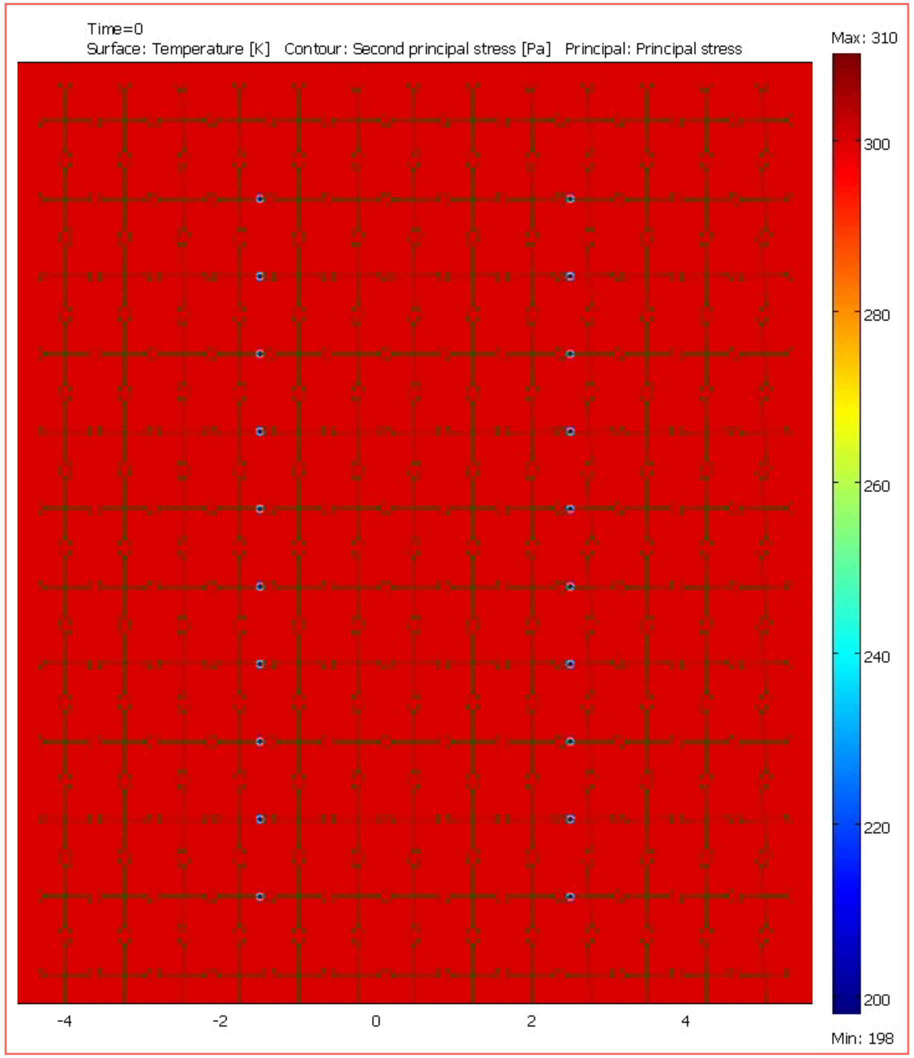
    1 m – 10^2 m
- Displacement during pressure change
    - a. stiffness vs. aperture
    - b. pressure dependant permeability
    - c. diagnostic tool (e.g. in situ fracture network characterization)

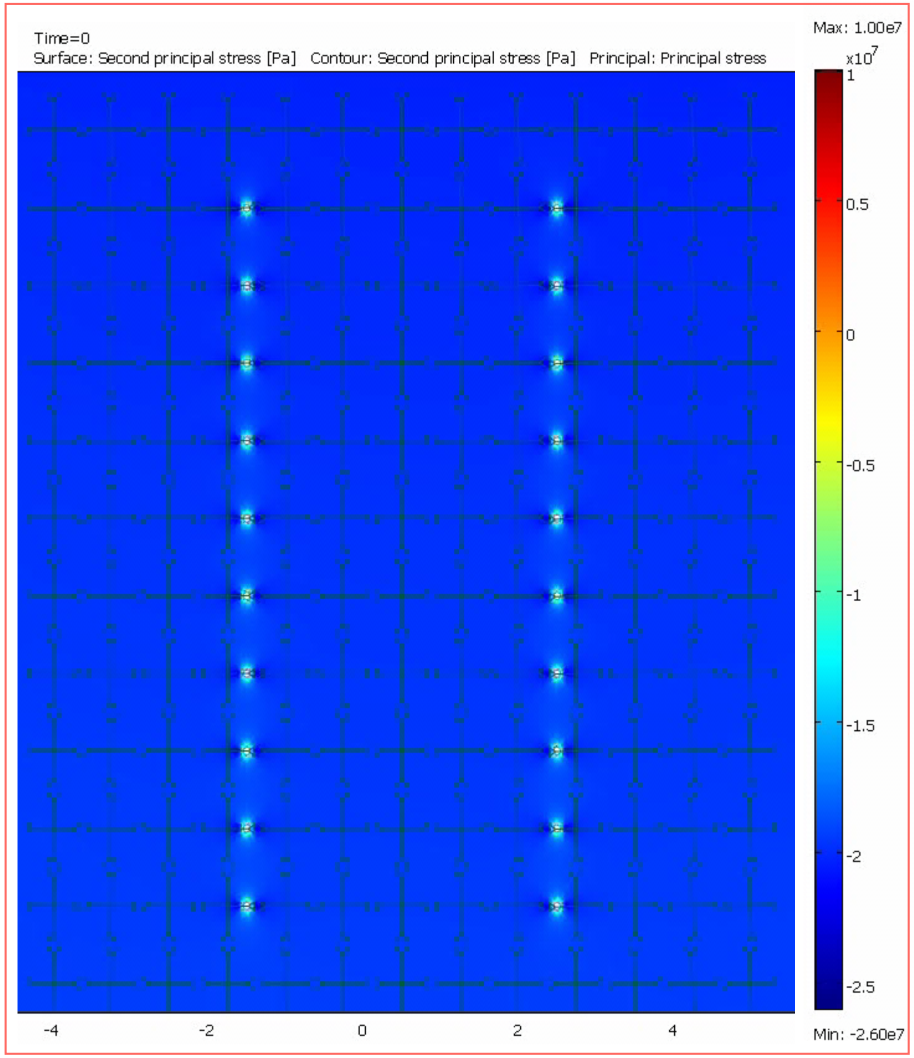
FEASIBILITY





FEASIBILITY





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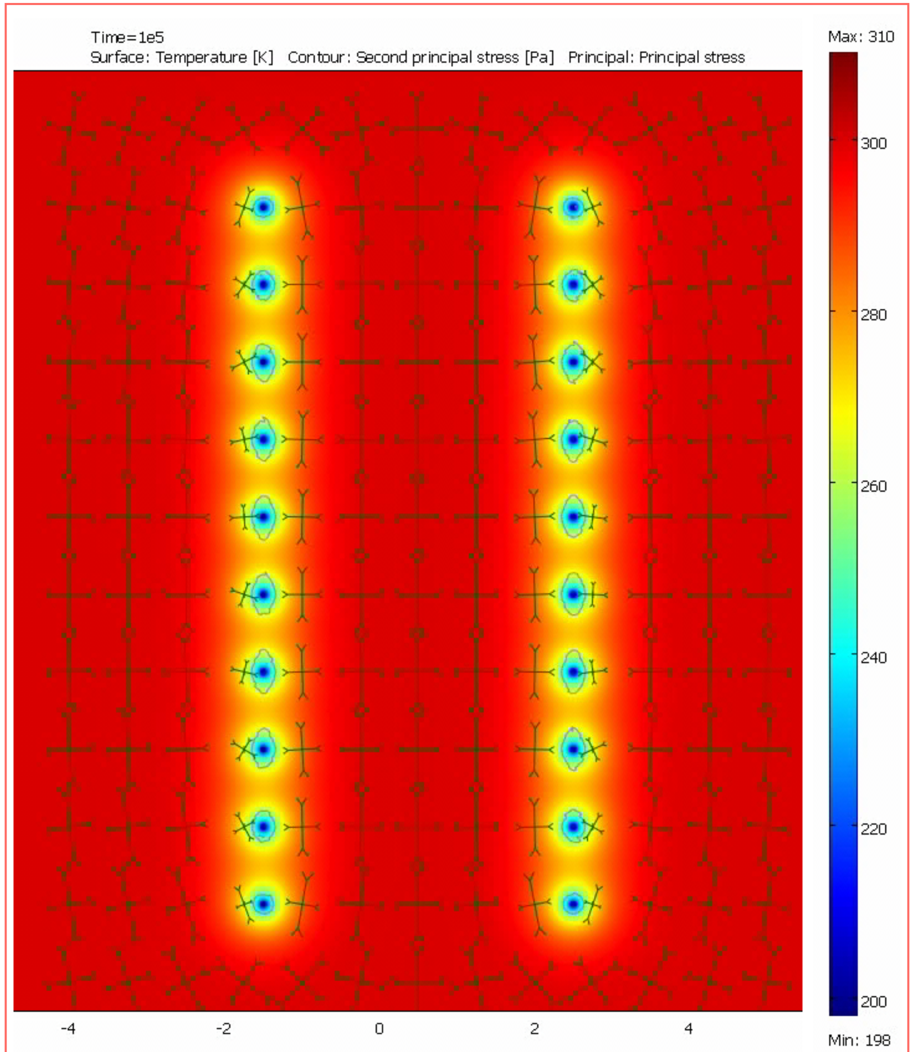
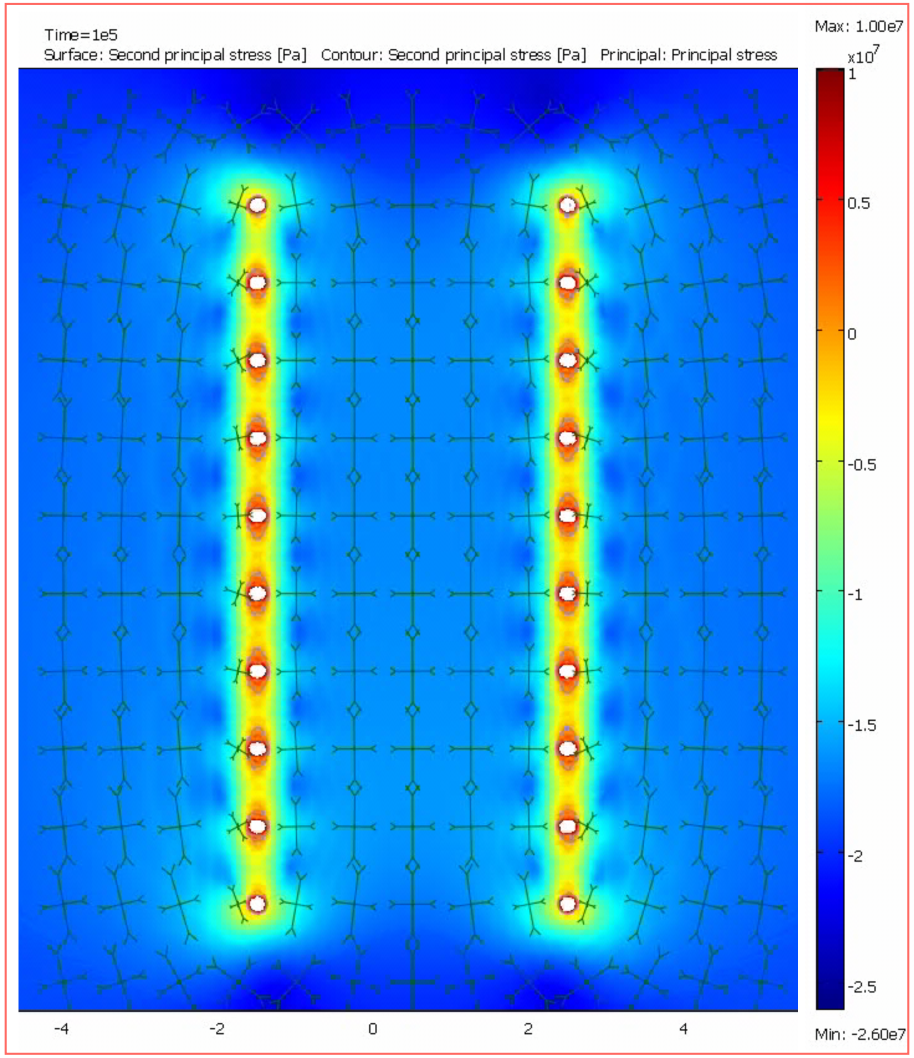
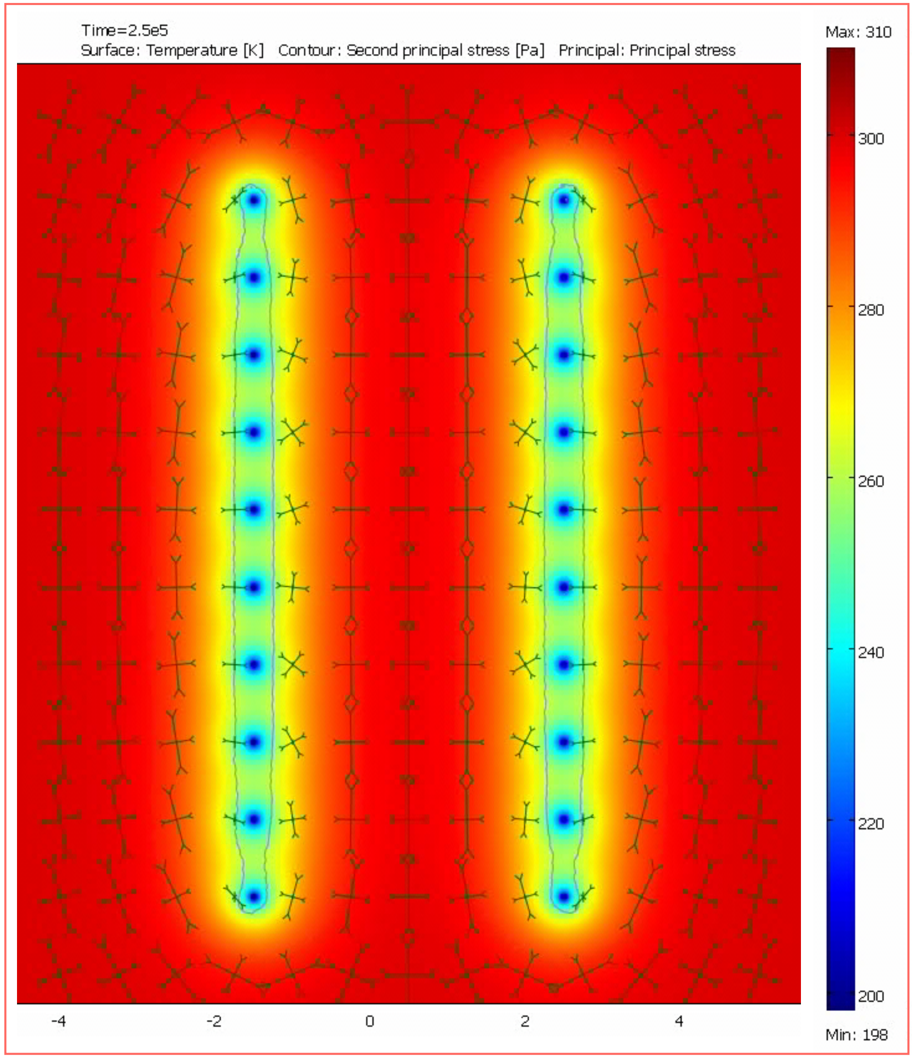
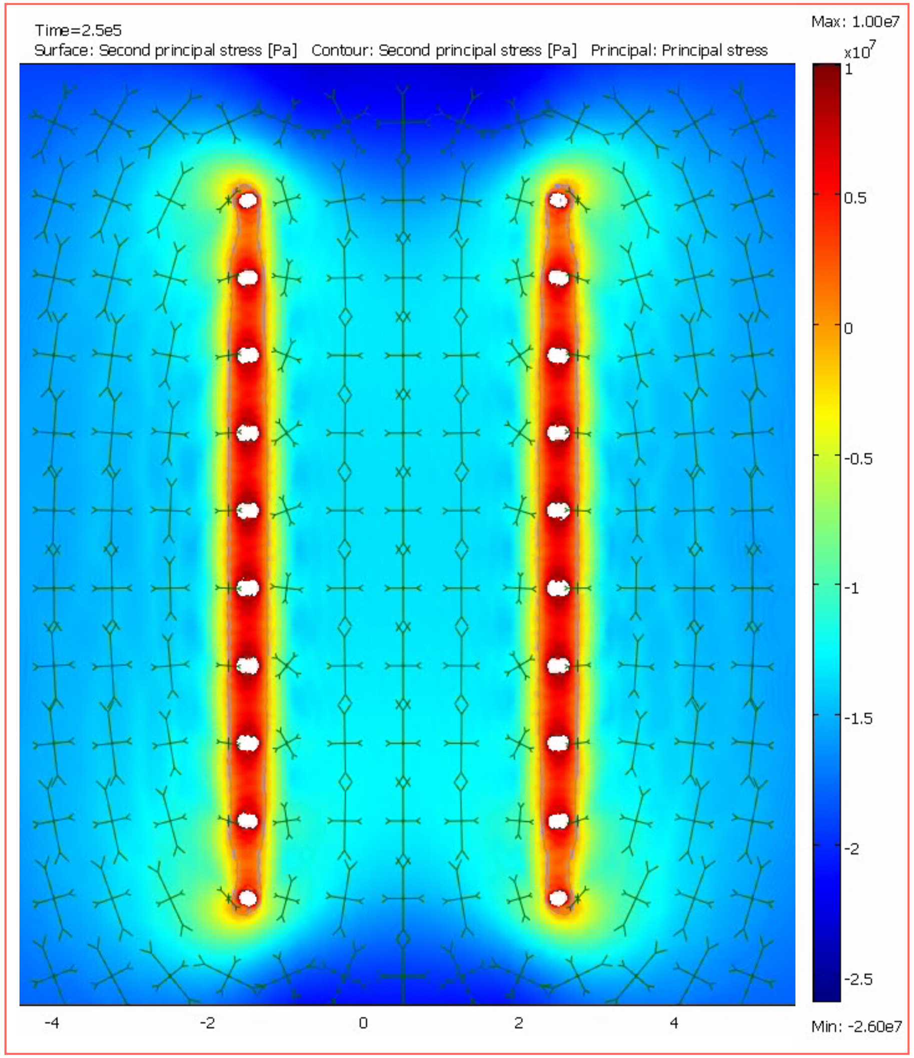




FEASIBILITY





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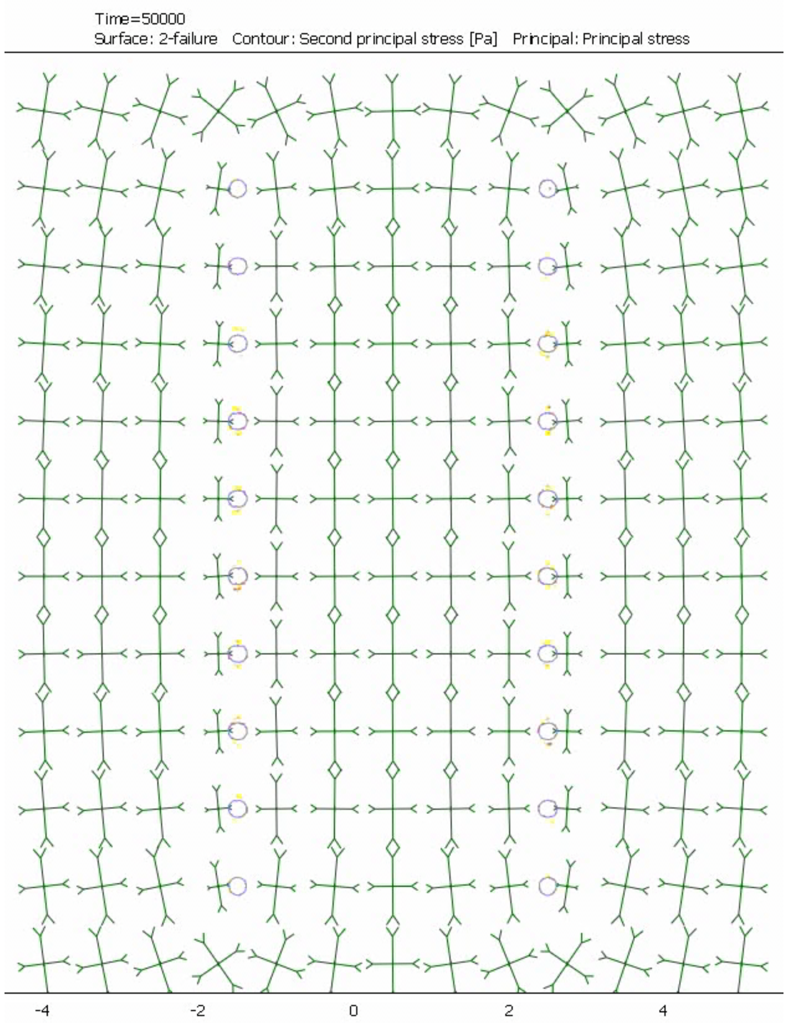
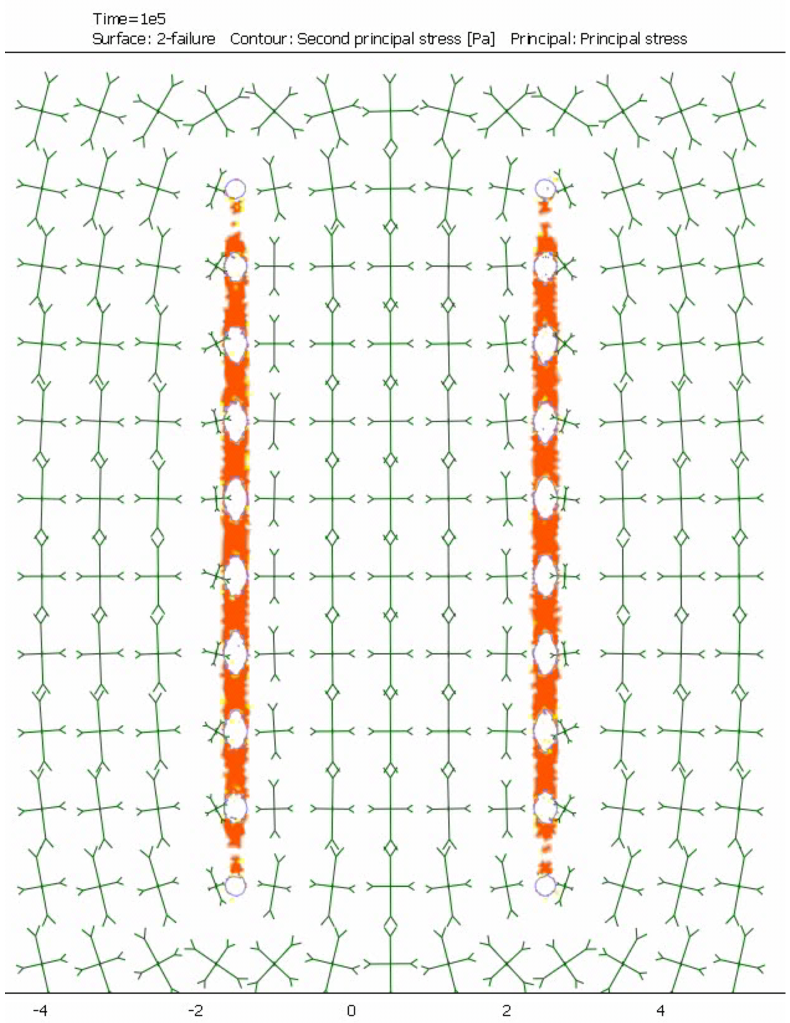




SUITE OF EXPERIMENTS

Big picture

- Fracture propagation
- Fluid flow in networks
- Deformable fractures
- Faulting
- Scaling of fracture energy
- Transport and reactions
- Microbiological processes during fracture

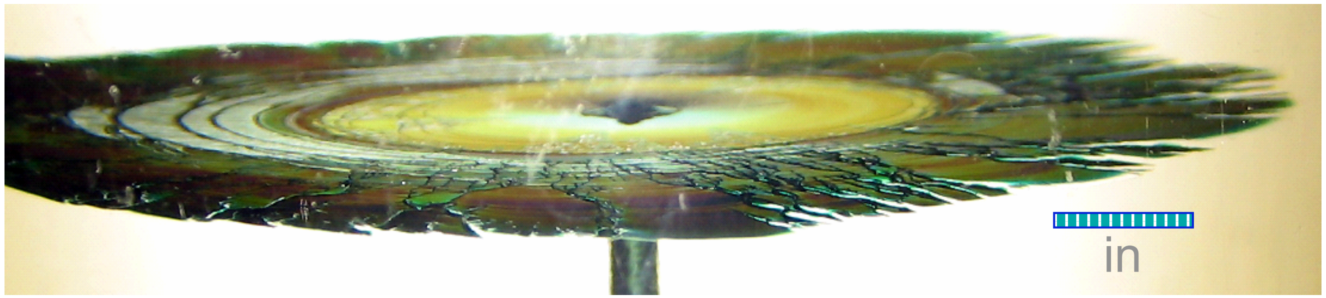
FRACTURE PROPAGATION EXPERIMENT

Methods

Hydraulic fracture in highly instrumented setting → excavate

Purpose

Evaluate and refine conceptual and theoretical models of Mode I fracture propagation in rock.



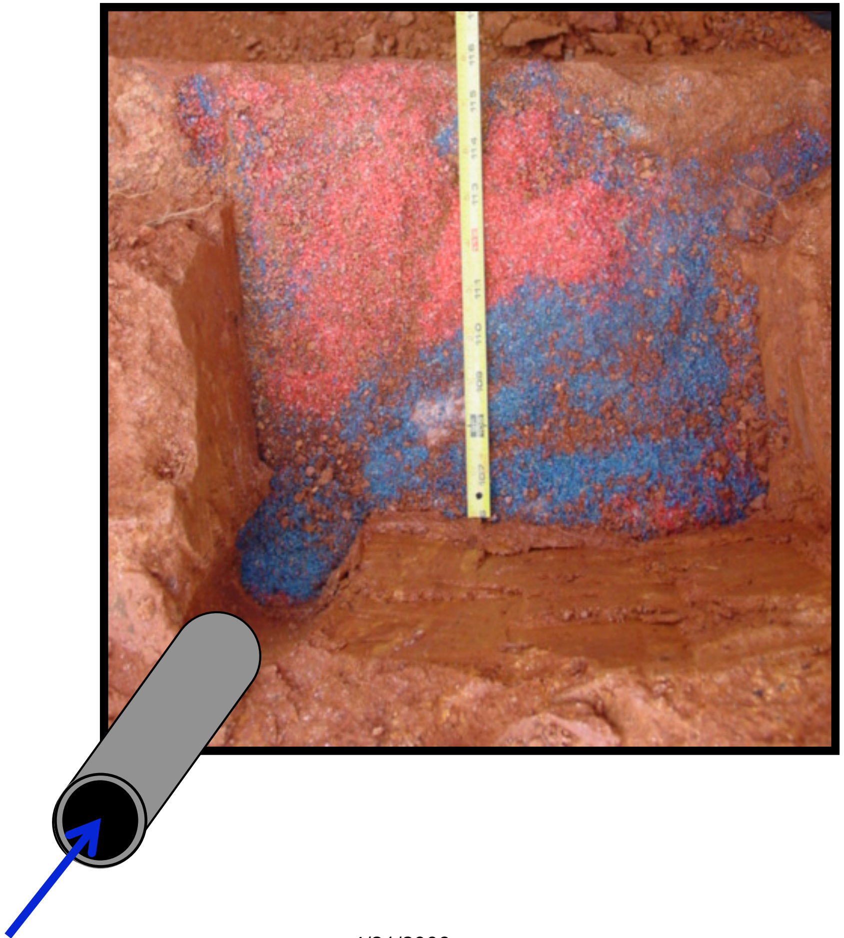
Tip

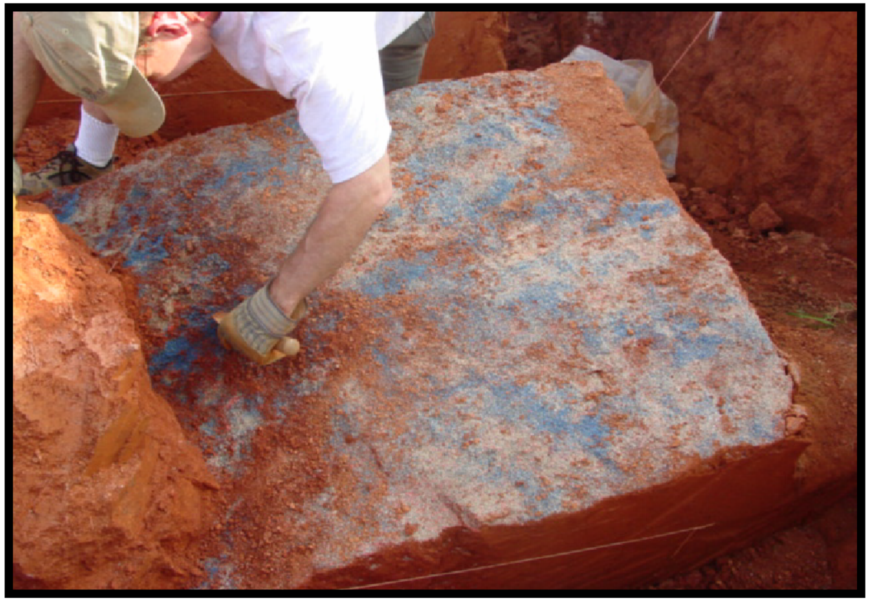
fluid lag
segmentation
heterogeneities
scaling

PROPAGATION EXPERIMENT (CONTINUED)

Fracture body

- fluid flow
- channeling
- transport of solids





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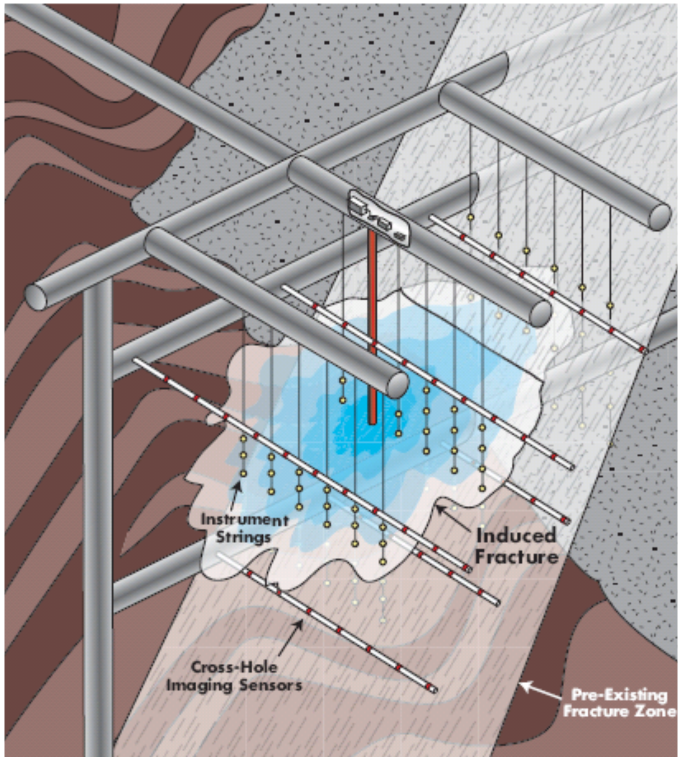
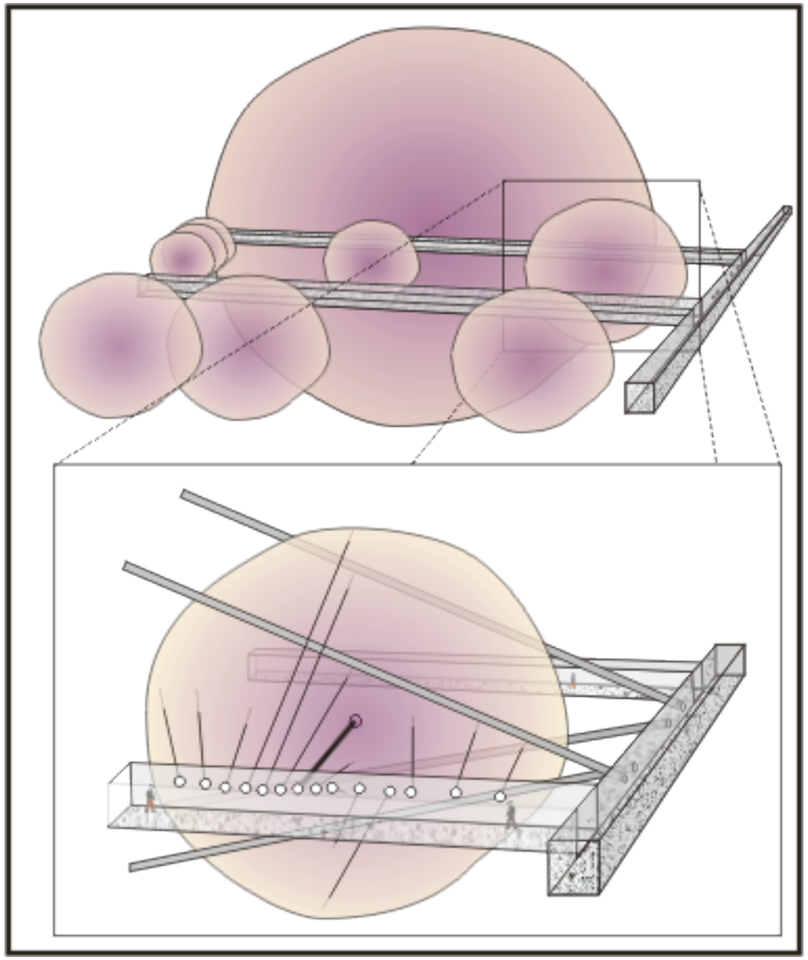


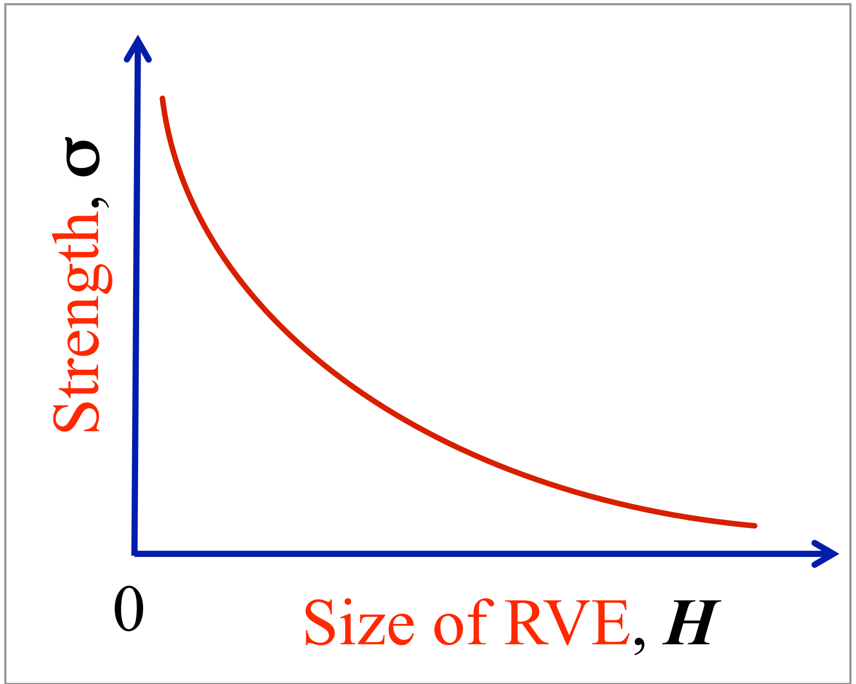


SCALE EFFECT IN ROCK PROPERTIES

One-Parametric Approach

$$\sigma = \sigma(H) \quad \rightarrow \quad \sigma = cH^{-d}$$

Power law follows directly from the assumption that strength is a function of only one parameter, *H*

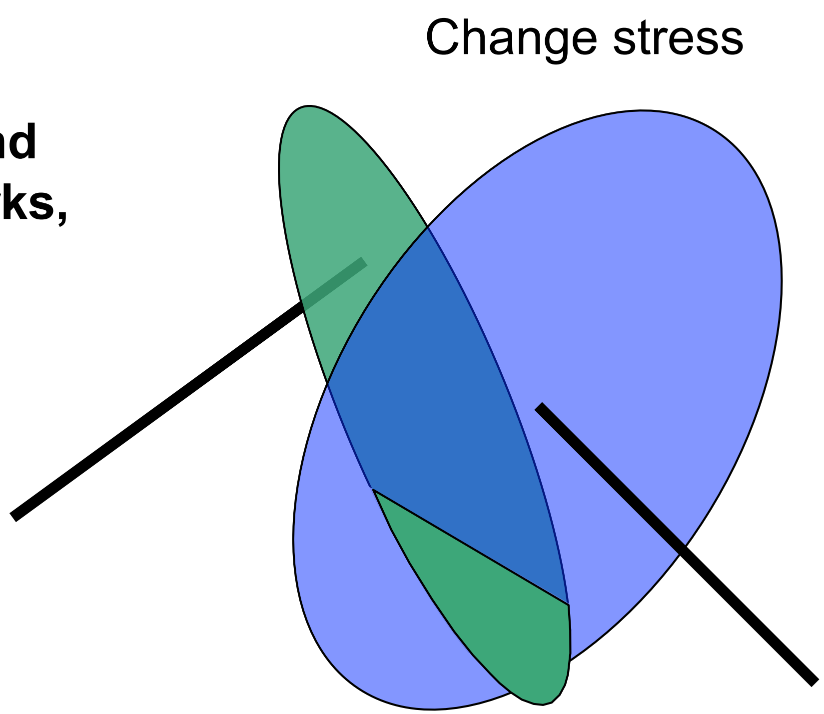


- essentially, dimensional analysis
- for strength, $d > 0$
- can be any property, not only strength
- various limitations – well recognized
- e.g., only one parameter or $\infty > H > 0$
- a large body of ongoing work
- many generalizations

SCALING OF FRACTURE ENERGY EXPERIMENT

Scale		Fracture energy (J/m^2)		Strength (MPa)
Lab (m)		10^2		100
Dikes-veins-hydraulic fractures (up to km)		10^4- 10^5		10
Mid-ocean segments, deep crustal faults (100 km)		10^7- 10^9		1

FRACTURE NETWORKS EXPERIMENT



Purpose: **Evaluate and refine conceptual and theoretical models involving fracture networks, including**

Fluid flow—onset of percolation
Mass transport
Chemical reactions
Heat transfer
Stress-deformation

Applications:

Veins
Water flow in deep rock
Hydrocarbons, geothermal
Waste Isolation
Remediation

SCALE EFFECT IN ROCK PROPERTIES

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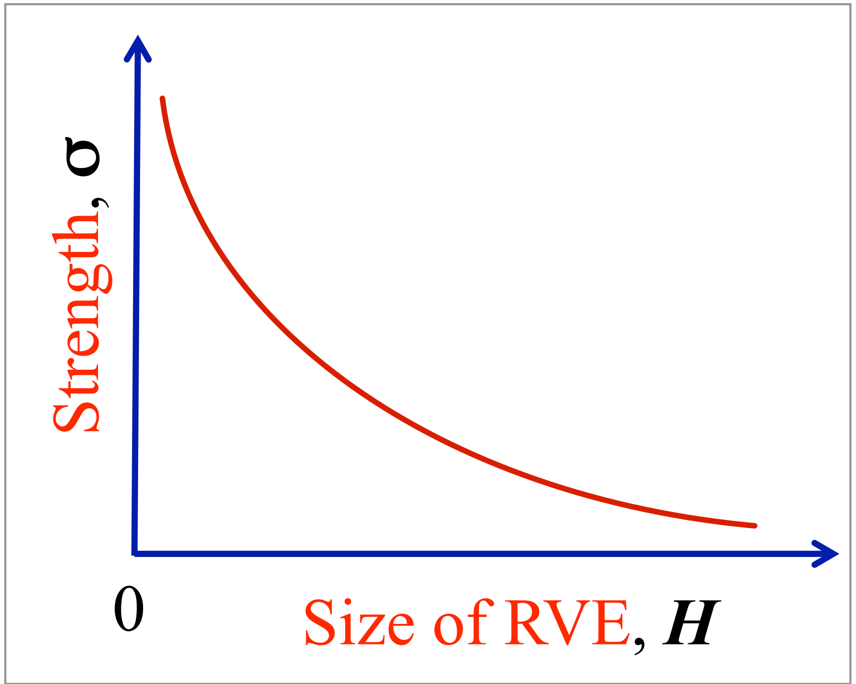

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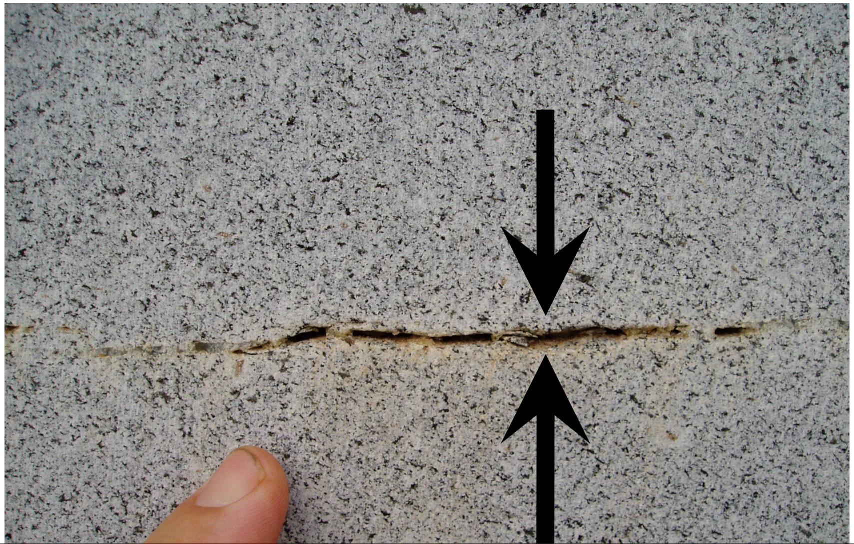
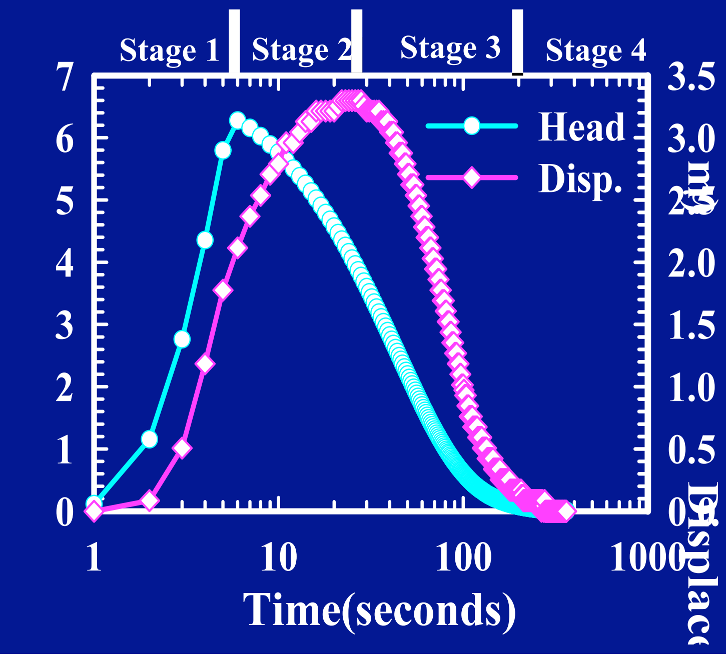
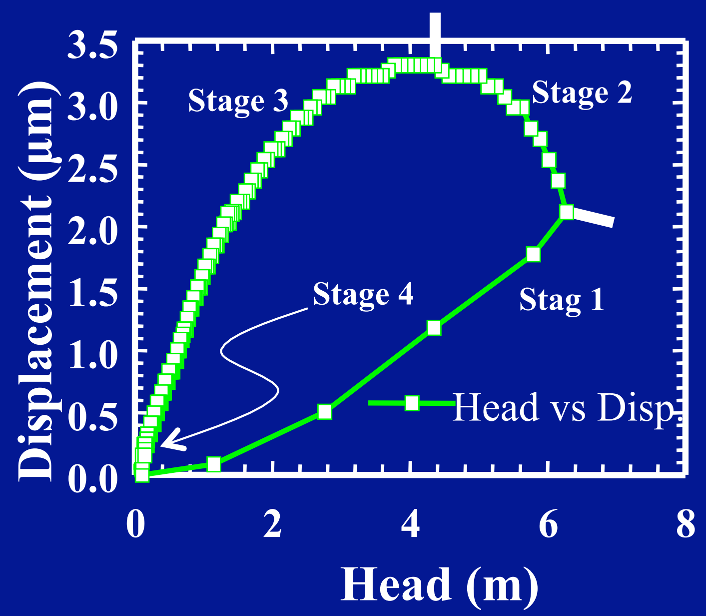
Displacement During Pressure Change Experiment

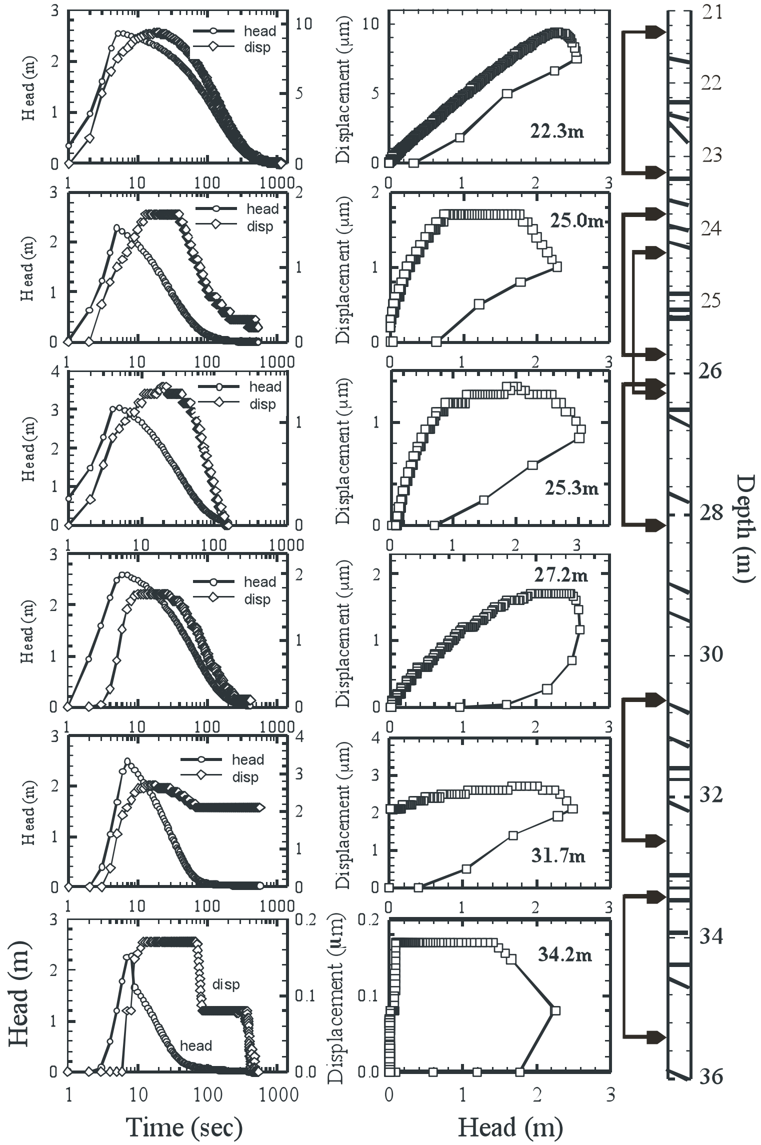
Hydromechanical well tests







HYDROMECHANICAL WELL TESTS



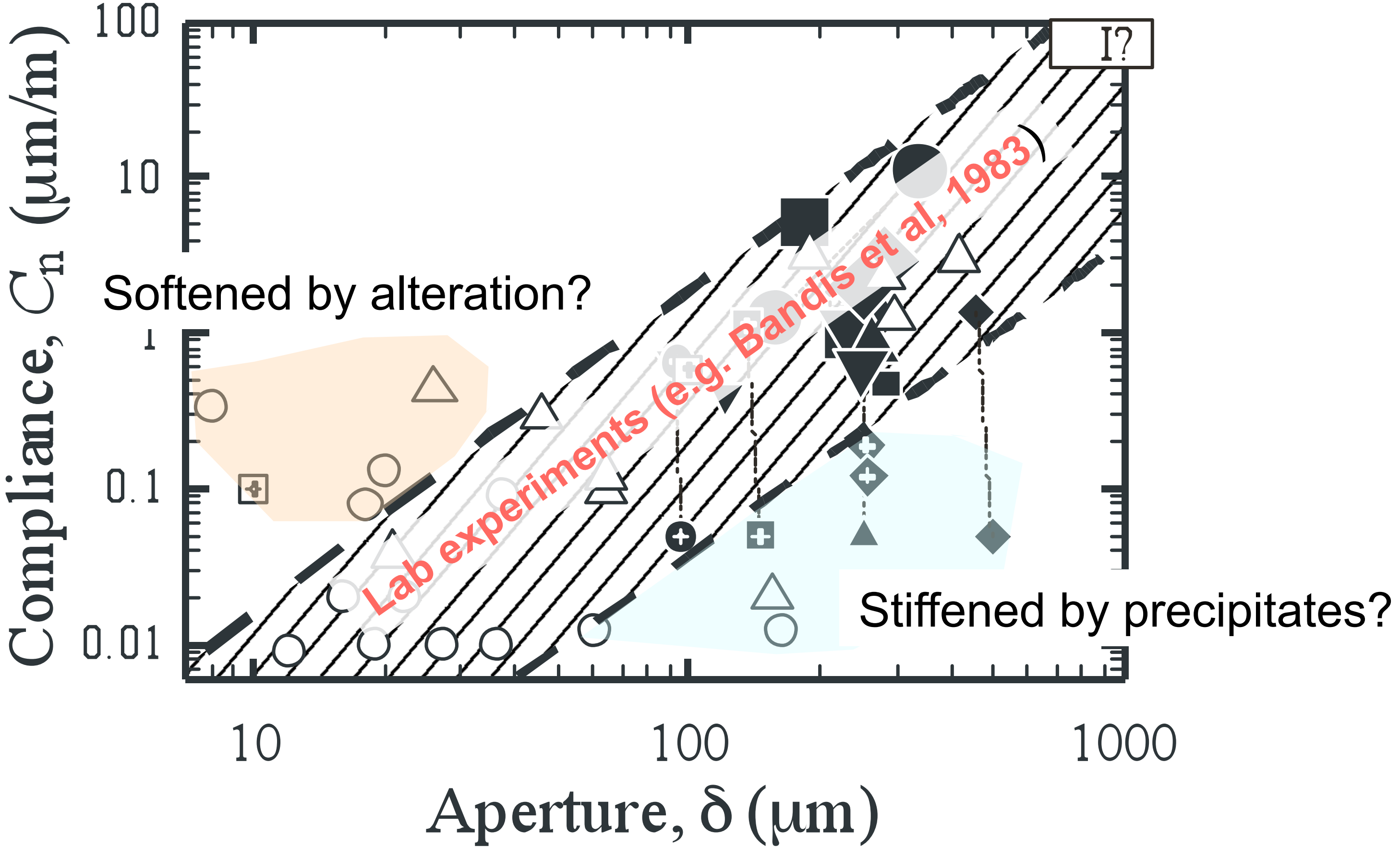
Distinctive response at different depths in a borehole.

Interpret to infer mechanical characteristics and fracture network geometry?

1. Use Fracture Lab to refine interpretation methods.

2. Apply to characterize accessible regions.

SCALING OF FRACTURE COMPLIANCE



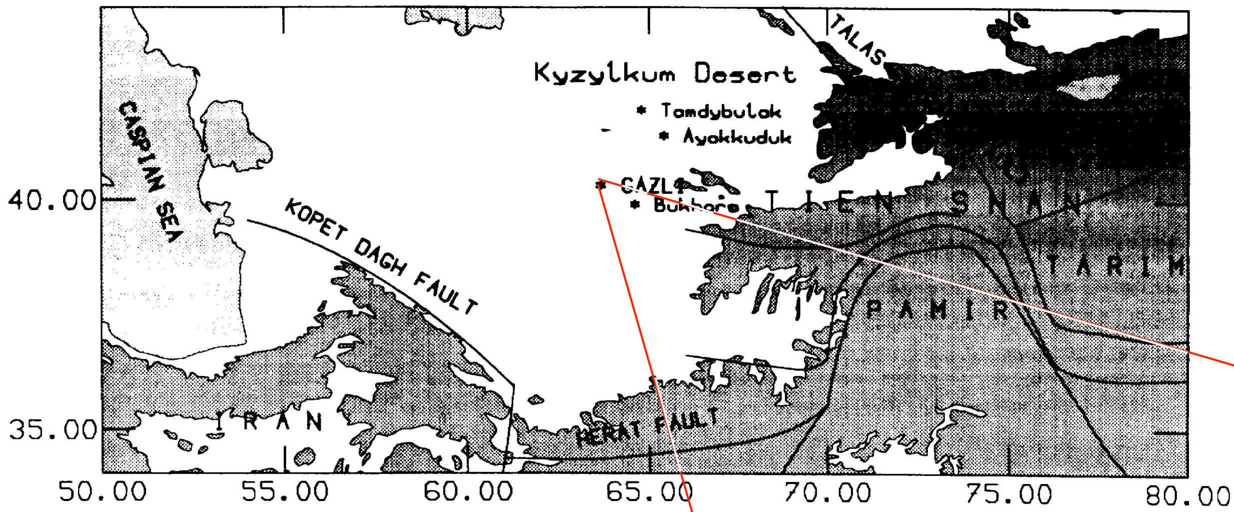
Data from Rutqvist et al, 1998; Martin et al. 1991, Cappa et al., 2006, Infanti et al., 1978, and this work

1. General field scaling of compliance and aperture?
2. Diagnostic tool for unusual fractures?

FAULT REACTIVATION AND INDUCED SEISMICITY

Gazli Gas Field, Uzbekistan

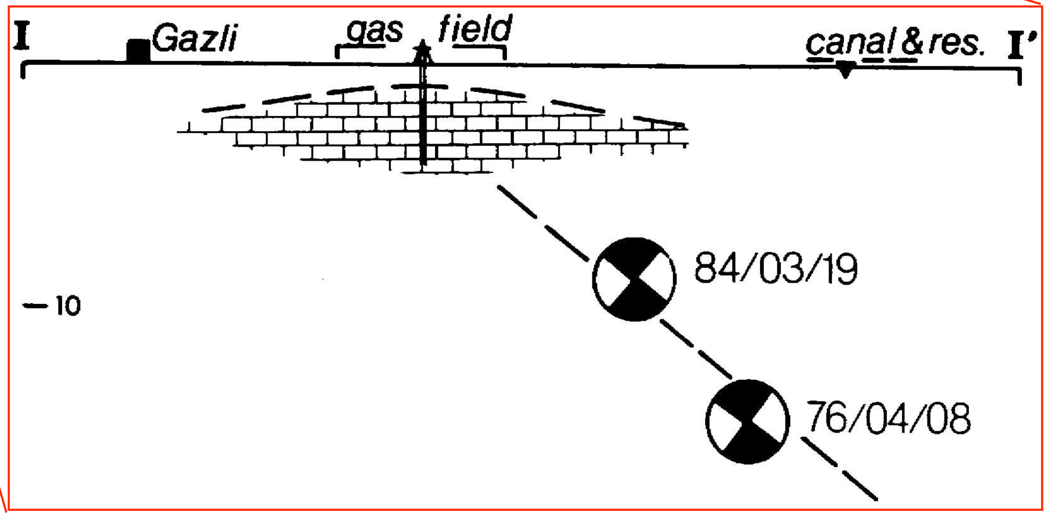
11,264 AMORESE AND GRASSO: GAZLI STRESSES AND SEISMIC RUPTURE GEOMETRIES



$M = 7+$

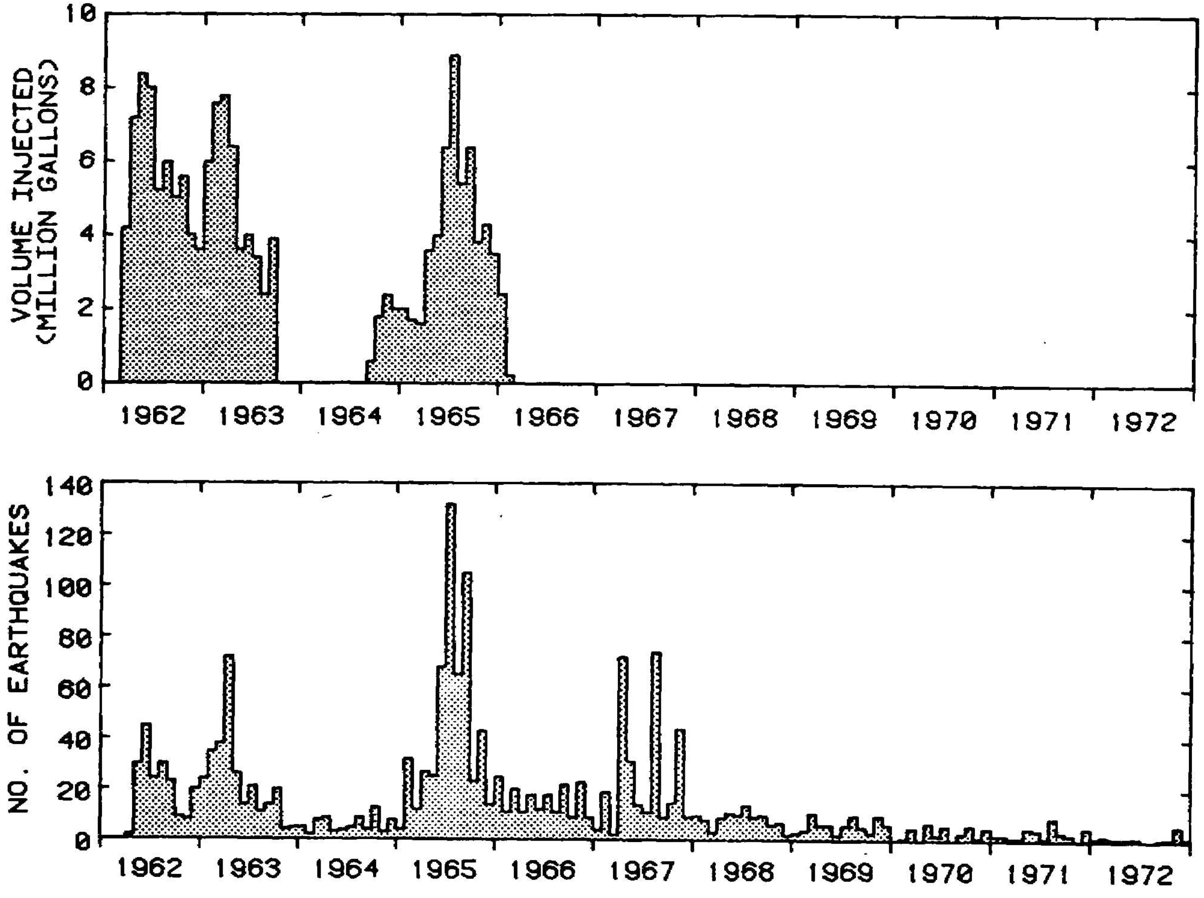
Amorèse and Grasso (1996)

Simpson and Leith (1985)



INJECTION INDUCED SEISMICITY

Denver Earthquakes



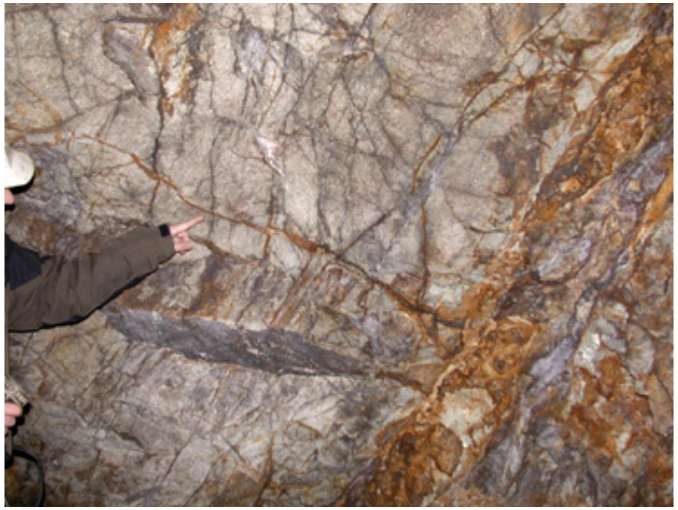
Three major earthquakes ($M > 5$) occurred in 1967, a year after waste disposal was stopped (Hsieh and Bredehoeft, 1981)

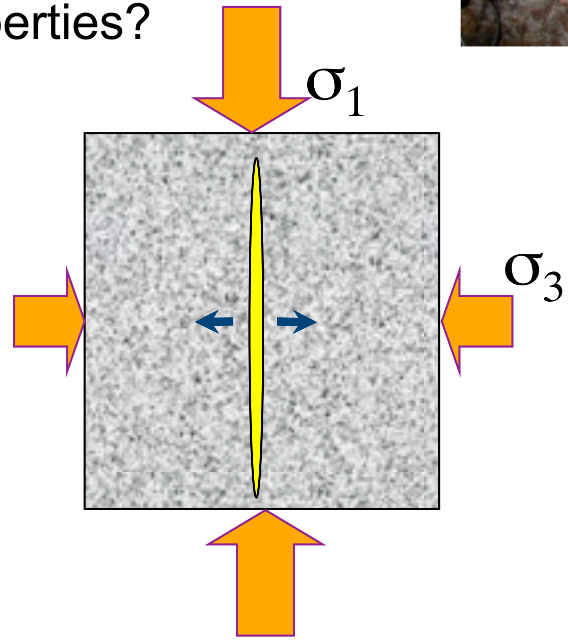
Current emphasis - Carbon Sequestration

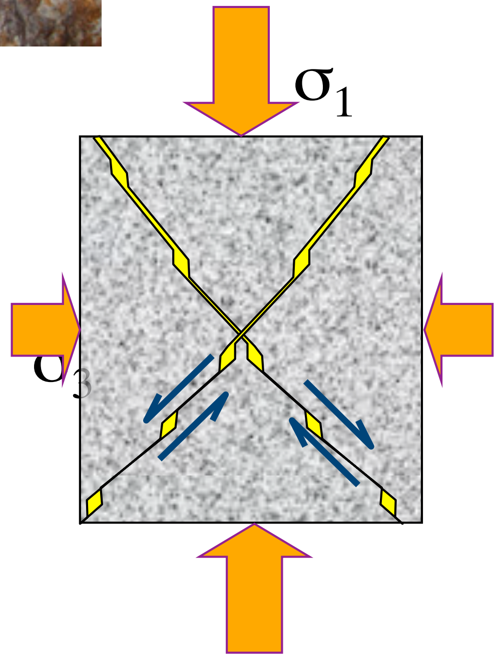
PERMEABILITY AND FAULT REACTIVATION

How do fractures develop into cluster of connected networks?

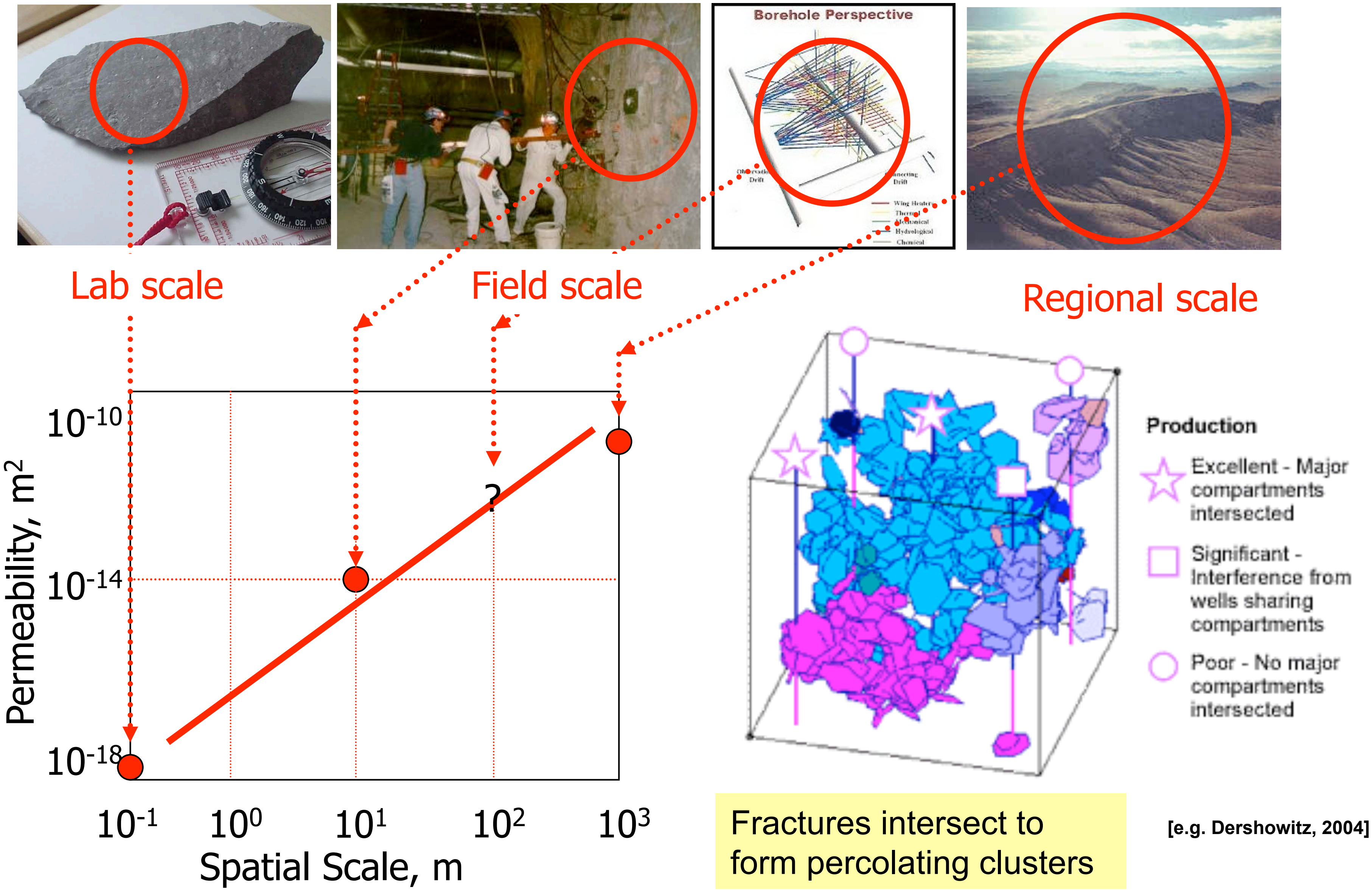
What controls the scale of the clusters, and how does stress affect properties?







SCALING OF PERMEABILITY IN FRACTURED ROCK



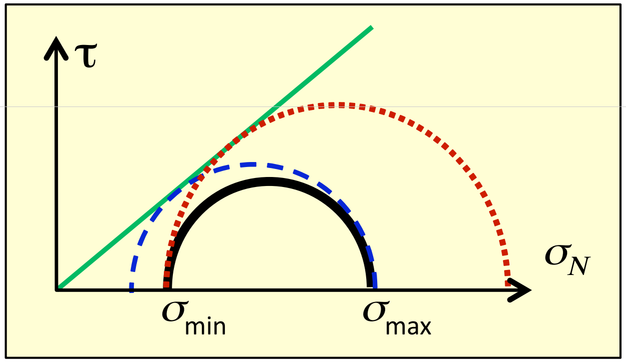
Fractures intersect to form percolating clusters

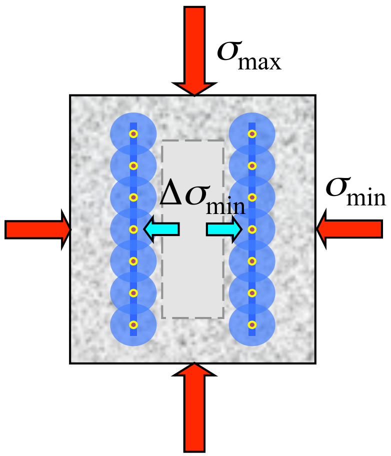
[e.g. Dershowitz, 2004]

Development of a Fracture Processes Facility at DUSEL Homestake

Approach

Faulting by thermally increasing or decreasing in-situ stress



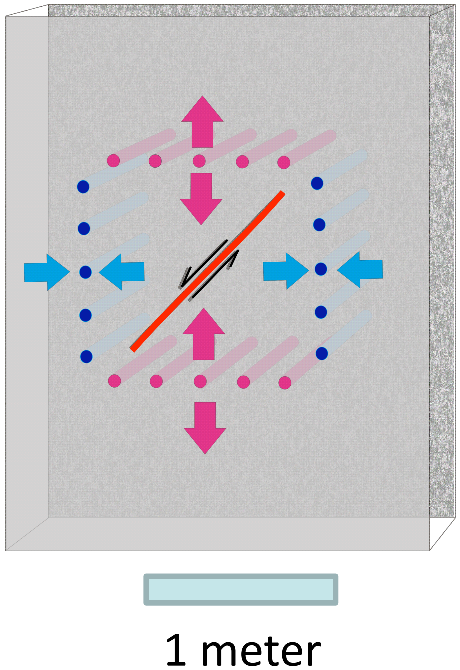


Cooling two rows of boreholes to change in-situ stress and cause faulting

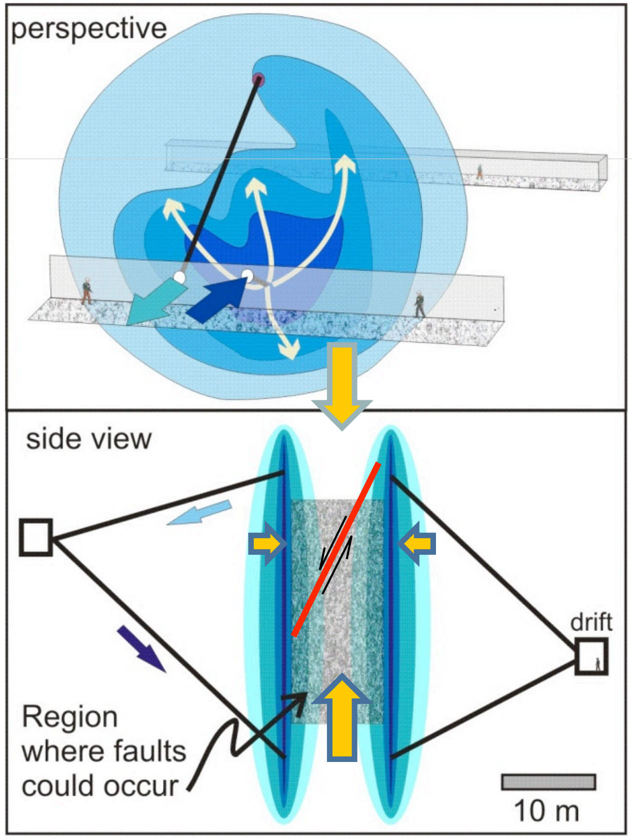
Facilities

Thermal panels to manipulate stresses

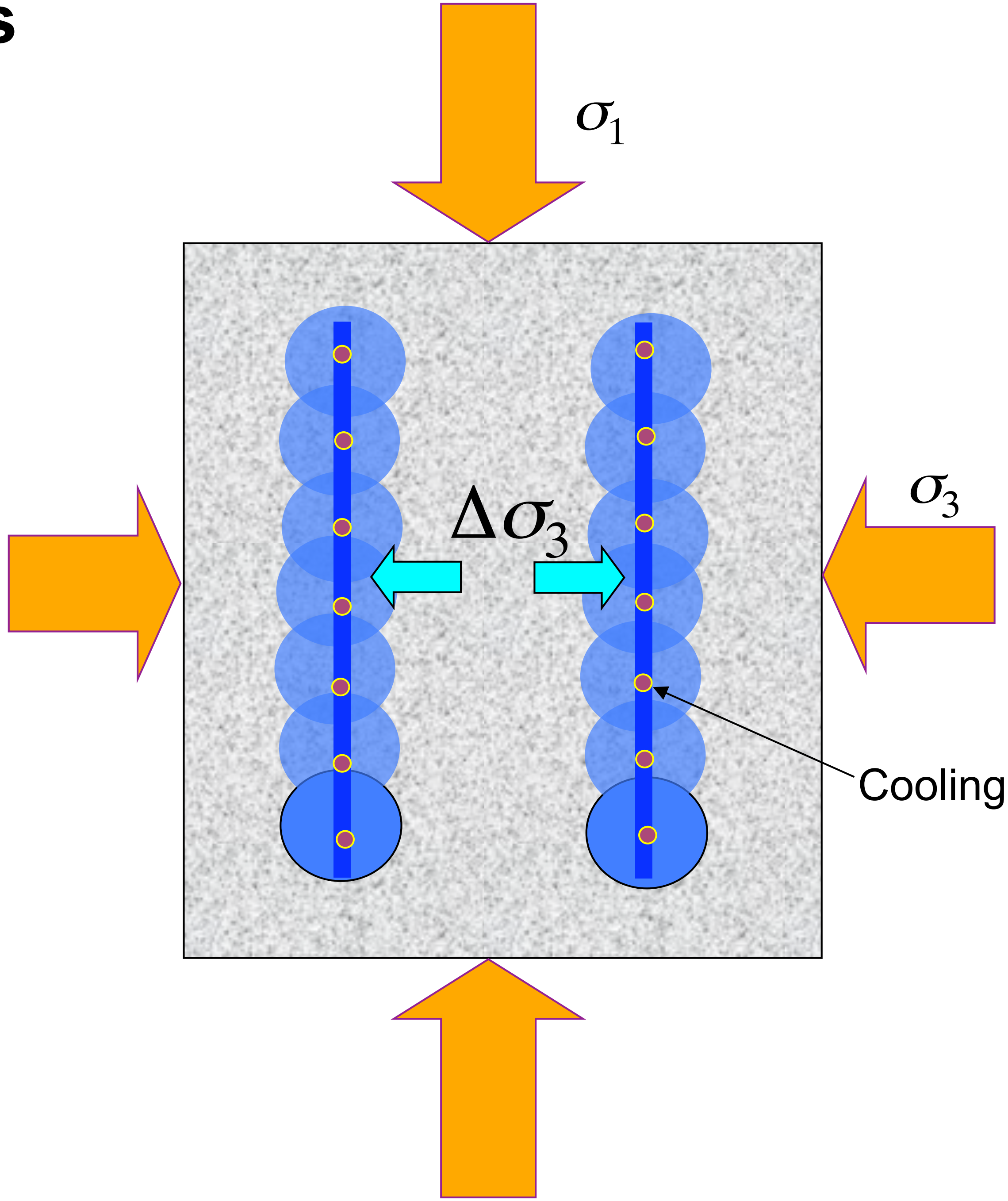
300′ Level Facility



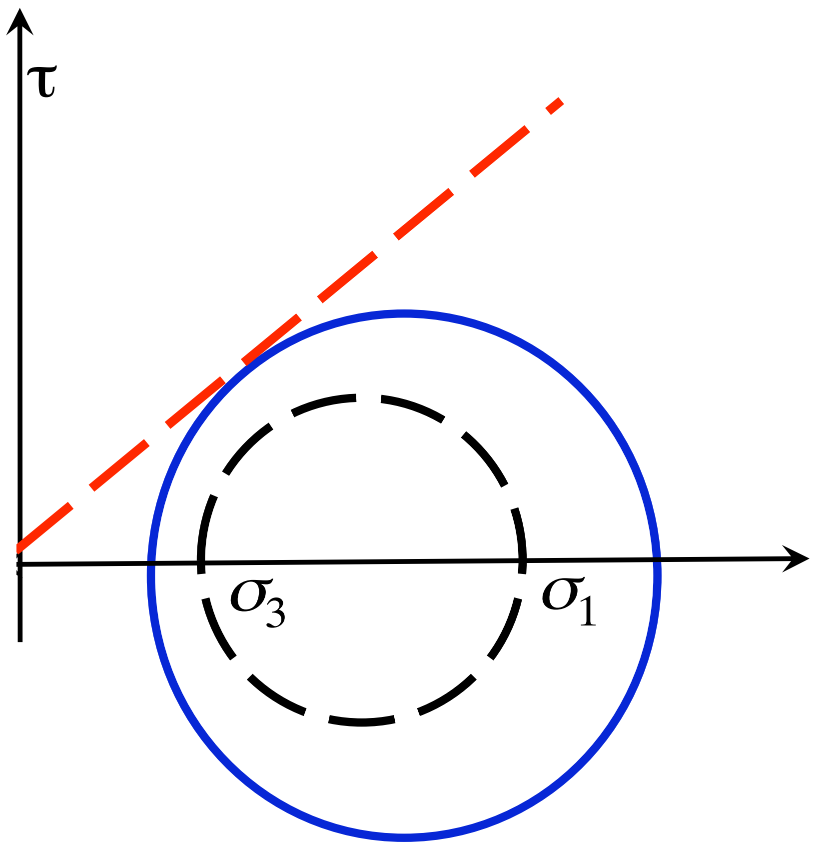
Deep Facility

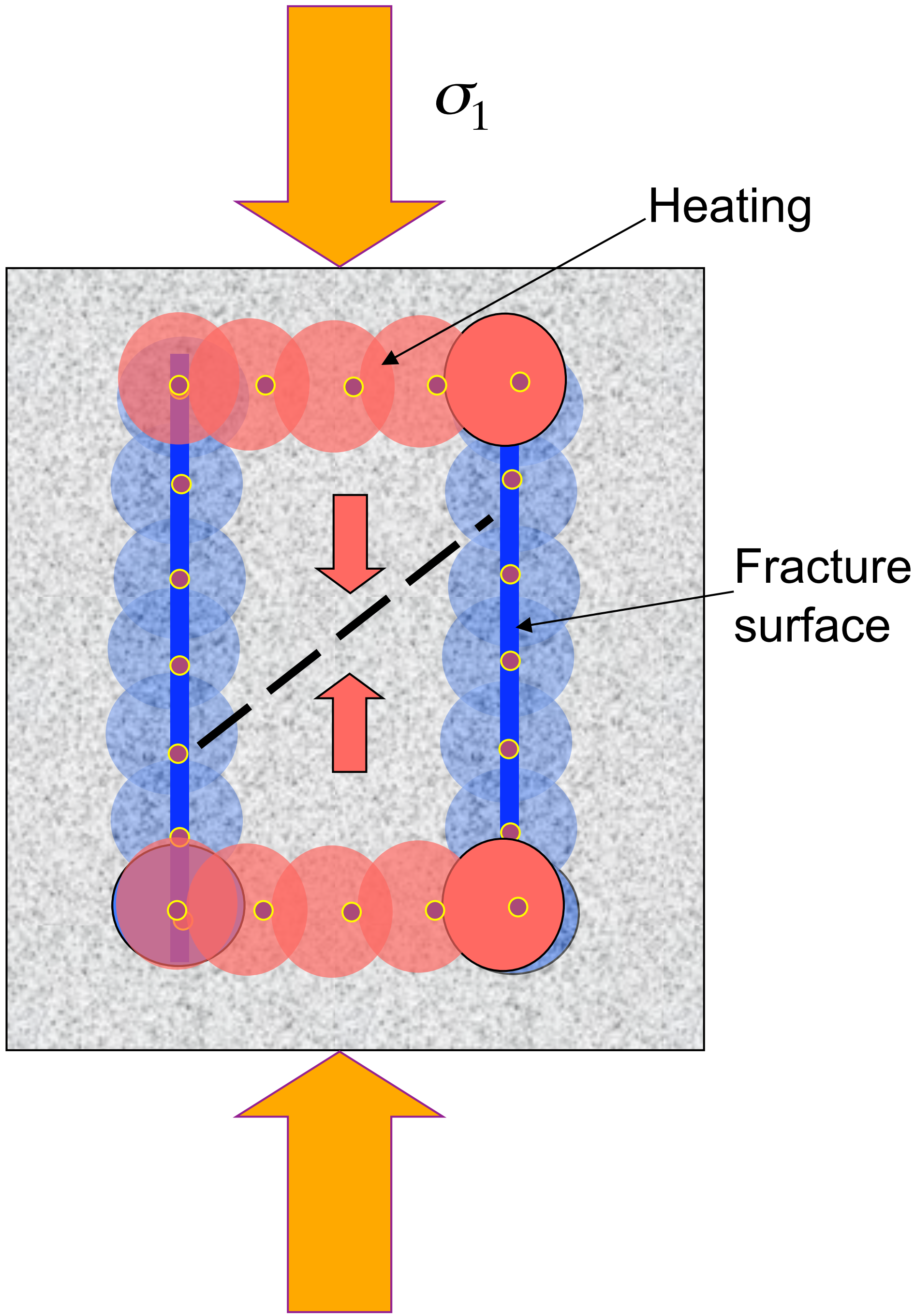


Fault experiments at 300 ft level



Fault experiments at 300 ft level





EXPERIMENTAL PROGRAM AND SCHEDULE

Integrated, phased suite of experiments to advance understanding of fault processes

Stage 1 – Pilot Tests

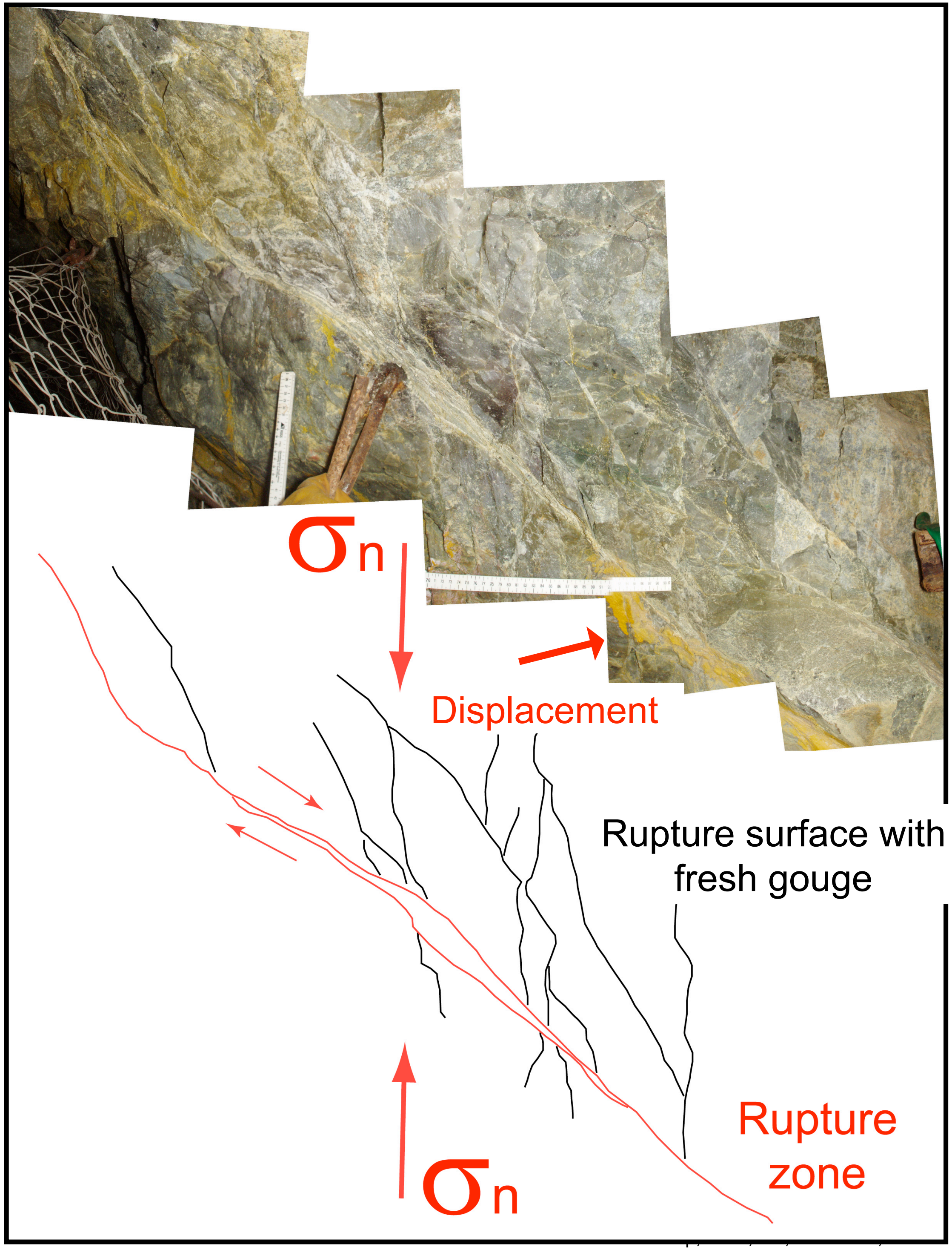
- Development experiments at 300 ft. level
- Mine back experiments during the construction phase
- Engineering Group (Chris Laughton)
- 1 to 2 years

Stage 2 – Development of Fault Processes Laboratory

- 2 years

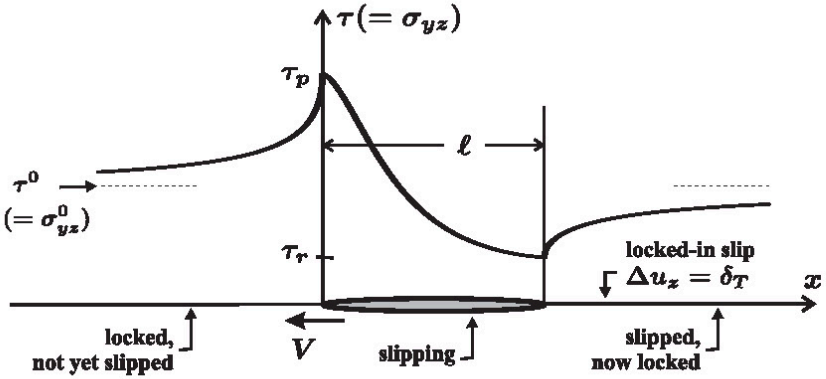
Stage 3 – Fault Characterization

- 3 years
- In collaboration with other groups


σn
Displacement
Rupture surface with
fresh gouge
Rupture
zone
σn

Dynamic Slip Propagation

Garagash [2007-2009]



Event & depth range	δ (m)	ℓ (km)	V (km / s)	$\overline{\Delta\sigma}_p$ (MPa)
Michoacan 1988 10 – 35 km (est)	2.8	13	2.6	1.4
Borah Peak 1983 0 – 15 km (est)	0.96	1.7	2.9	2.6
San Fernando 1971 3 – 15 km	1.4	2.2	2.8	4.
Imperial Valey 1979 0 – 10 km	0.56	2.6	2.6	1.3
Morgan Hill 1984 0 – 12 km	0.44	0.8	2.8	3.2
N. Palm Springs 1986 1 – 12 km	0.33	1.2	3	1.2
Coyote Lake 1979 3 – 10 km	0.32	1.4	2.8	2.2

Parameter values used for matching:

$$\mu = 30\ \text{GPa}, \qquad \tau_p = f \text{ x } 18\frac{\text{MPa}}{\text{km}} \text{ x } \textit{median depth}$$

$$f = 0.125, \qquad \delta_c = \frac{\rho c}{f\Lambda}h \approx \frac{3}{f}h = 1\ \text{m} \qquad (\Rightarrow h = 42\ \text{mm})$$

$$\bar{\mu} = \mu\sqrt{1-(V/c_s)^2}$$